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Schwarz et al.

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(45) **Date of Patent: *Mar. 15, 2022**

(54) **BOWED ROTOR START MITIGATION IN A GAS TURBINE ENGINE USING AIRCRAFT-DERIVED PARAMETERS**

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(73) Assignee: **RAYTHEON TECHNOLOGIES CORPORATION**, Farmington, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 61 days.

This patent is subject to a terminal disclaimer.

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(65) **Prior Publication Data**

US 2020/0291860 A1 Sep. 17, 2020

Related U.S. Application Data

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(51) **Int. Cl.**

F01D 19/02 (2006.01)
F01D 25/34 (2006.01)
(Continued)

(52) **U.S. Cl.**

CPC ***F02C 7/27*** (2013.01); ***F01D 19/02*** (2013.01); ***F01D 25/24*** (2013.01); ***F01D 25/34*** (2013.01);
(Continued)

(58) **Field of Classification Search**

CPC F01D 19/02; F01D 25/34; F02C 7/268; F05D 2260/85; F05D 2270/114; F05D 2270/304; F05D 2270/334
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,951,875	A	3/1934	Laabs
2,617,253	A	11/1952	Fusner et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP	1396611		3/2004
EP	1533479	A2	5/2005

(Continued)

OTHER PUBLICATIONS

EP Application No. 17155584 Extended European Search Report dated Jul. 6, 2017, 9 pages.

(Continued)

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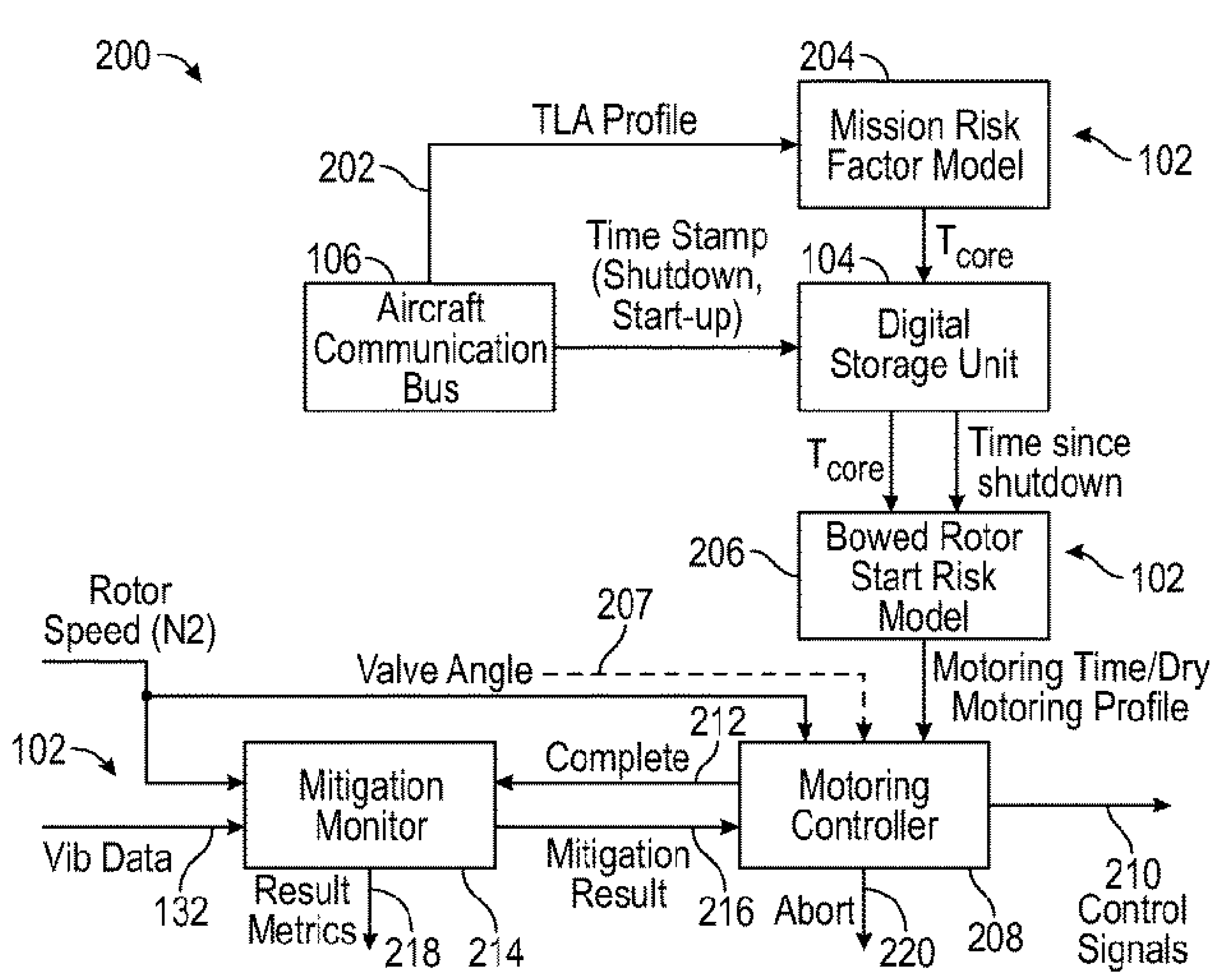
(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP

(57) **ABSTRACT**

A bowed rotor start mitigation system for a gas turbine engine of an aircraft is provided. The bowed rotor start mitigation system includes a motoring system and a controller coupled to the motoring system and an aircraft communication bus. The controller is configured to determine at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The motoring system is controlled to drive rotation of a starting spool of the gas turbine engine below an engine
(Continued)



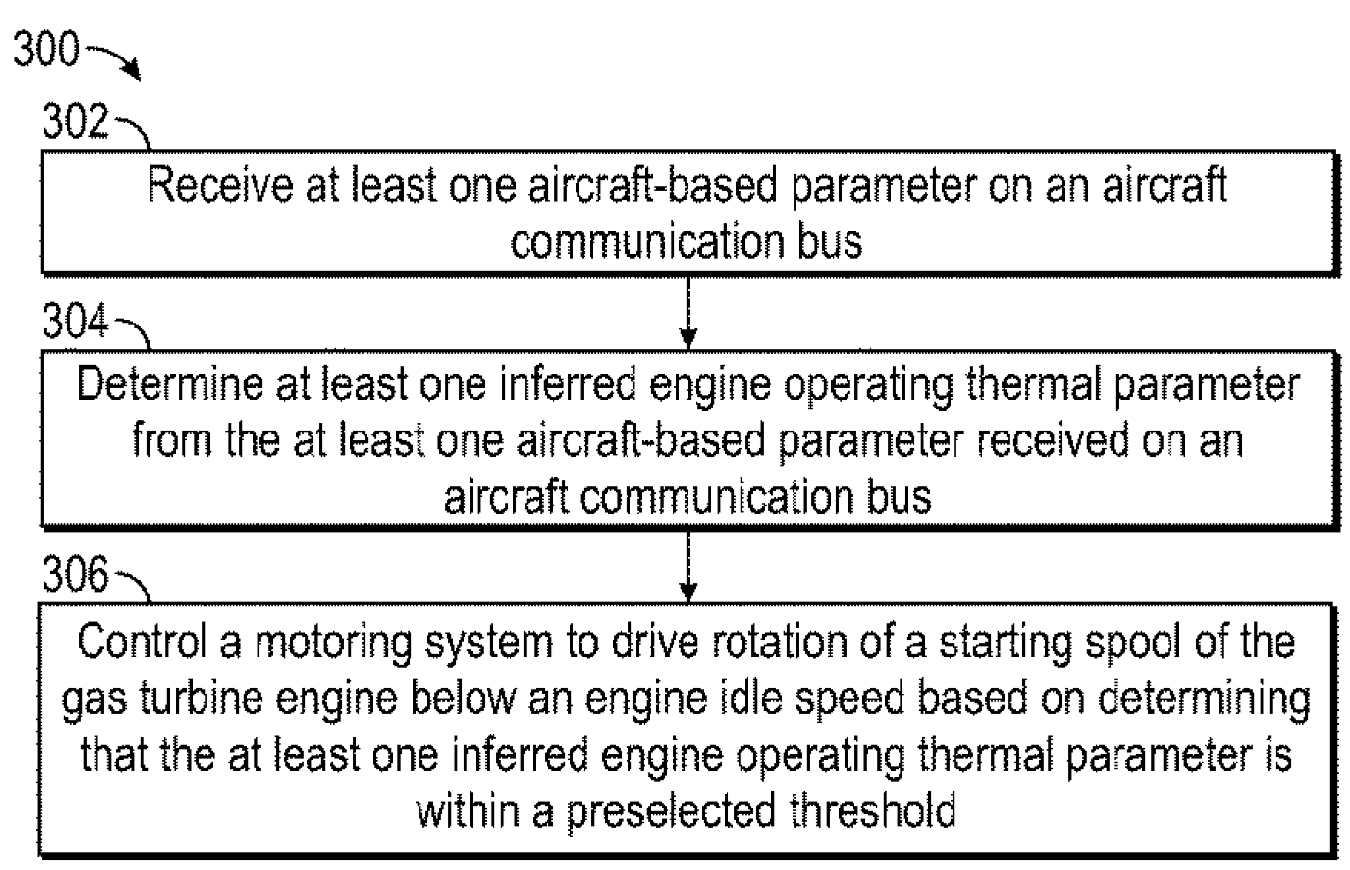


FIG. 5

idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

20 Claims, 8 Drawing Sheets

(51) **Int. Cl.**
F02C 7/27 (2006.01)
F02C 7/268 (2006.01)
F01D 25/24 (2006.01)
F02C 3/107 (2006.01)
F02C 7/06 (2006.01)
F02K 3/04 (2006.01)
G05B 15/02 (2006.01)

(52) **U.S. Cl.**
CPC ***F02C 3/107*** (2013.01); ***F02C 7/06*** (2013.01); ***F02C 7/268*** (2013.01); ***F02K 3/04*** (2013.01); ***G05B 15/02*** (2013.01); *F05D 2220/323* (2013.01); *F05D 2260/85* (2013.01); *F05D 2270/021* (2013.01); *F05D 2270/114* (2013.01); *F05D 2270/304* (2013.01); *F05D 2270/334* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,962,597 A 11/1960 Evans
3,057,155 A 10/1962 Rizk
3,151,452 A 10/1964 Bunger et al.
3,290,709 A 12/1966 Whitenack, Jr. et al.
3,360,844 A 1/1968 Wonneman
3,764,815 A 10/1973 Habock et al.
3,793,905 A 2/1974 Black et al.
3,898,439 A 8/1975 Reed et al.
3,951,008 A 4/1976 Schneider et al.
4,044,550 A 8/1977 Vermilye
4,069,424 A 1/1978 Burkett
4,120,159 A 10/1978 Matsumoto et al.
4,144,421 A 3/1979 Sakai
4,302,813 A 11/1981 Kurihara et al.
4,353,604 A 10/1982 Dulberger et al.
4,380,146 A 4/1983 Yannone et al.
4,426,641 A 1/1984 Kurihara et al.
4,435,770 A 3/1984 Shiohata et al.
4,437,163 A 3/1984 Kurihara et al.
4,453,407 A 6/1984 Sato et al.
4,485,678 A 12/1984 Fanuele
4,488,240 A 12/1984 Kapadia et al.
4,496,252 A 1/1985 Horler et al.
4,598,551 A 7/1986 Dimitroff, Jr. et al.
4,627,234 A 12/1986 Schuh
4,642,782 A 2/1987 Kemper et al.
4,669,893 A 6/1987 Chalaire et al.
4,713,985 A 12/1987 Ando
4,733,529 A 3/1988 Nelson et al.
4,747,270 A 5/1988 Klie et al.
4,854,120 A 8/1989 Nelson et al.
4,856,272 A 8/1989 Putman et al.
4,862,009 A 8/1989 King
4,979,362 A 12/1990 Vershure, Jr.
5,103,629 A 4/1992 Mumford et al.
5,123,239 A 6/1992 Rodgers
5,127,220 A 7/1992 Jesrai et al.
5,174,109 A 12/1992 Lampe
5,184,458 A 2/1993 Lampe et al.
5,201,798 A 4/1993 Hogan
5,349,814 A 9/1994 Ciokajlo et al.
5,388,960 A 2/1995 Suzuki et al.
6,146,090 A 11/2000 Schmidt
6,168,377 B1 1/2001 Wolfe et al.
6,190,127 B1 2/2001 Schmidt
6,318,958 B1 11/2001 Giesler et al.
6,478,534 B2 11/2002 Bangert et al.
6,498,978 B2 12/2002 Leamy et al.
6,517,314 B1 2/2003 Burnett et al.
6,558,118 B1 5/2003 Brisson et al.
6,681,579 B2 1/2004 Lane et al.
6,762,512 B2 7/2004 Nelson
7,104,072 B2 9/2006 Thompson
7,133,801 B2 11/2006 Song
7,409,319 B2 8/2008 Kant et al.
7,428,819 B2 9/2008 Cataldi et al.
7,507,070 B2 3/2009 Jones
7,543,439 B2 6/2009 Butt et al.
7,587,133 B2 9/2009 Franke et al.
7,742,881 B2 6/2010 Muralidharan et al.
7,798,720 B1 9/2010 Walsh
7,909,566 B1 3/2011 Brostmeyer
7,972,105 B2 7/2011 Dejoris et al.
8,090,456 B2 1/2012 Karpman et al.
8,291,715 B2 10/2012 Libera et al.
8,306,776 B2 11/2012 Ihara et al.
8,770,913 B1 7/2014 Negron et al.
8,776,530 B2 7/2014 Shirooni et al.
8,820,046 B2 9/2014 Ross et al.
8,918,264 B2 12/2014 Jegu et al.
9,086,018 B2 7/2015 Winston et al.
9,121,309 B2 9/2015 Geiger
9,429,510 B2 8/2016 Belsom et al.
9,664,070 B1 5/2017 Clauson et al.
9,699,833 B2 7/2017 Broughton et al.
9,845,730 B2 12/2017 Betti et al.
9,970,328 B2 5/2018 Haerms et al.
9,988,928 B2 6/2018 Popescu et al.
10,040,577 B2 8/2018 Teicholz et al.
2002/0173897 A1 11/2002 Leamy et al.
2003/0145603 A1 8/2003 Reed et al.
2003/0209910 A1* 11/2003 Nelson F02C 7/268 290/52
2004/0065091 A1 4/2004 Anderson
2004/0131138 A1 7/2004 Correia et al.
2006/0032234 A1 2/2006 Thompson
2006/0188372 A1 8/2006 Hansen
2006/0260323 A1 11/2006 Moulebhar
2007/0031249 A1 2/2007 Jones
2007/0151258 A1 7/2007 Gaines et al.
2008/0072568 A1 3/2008 Moniz et al.
2009/0246018 A1 10/2009 Kondo et al.
2009/0301053 A1 12/2009 Geiger
2009/0314002 A1 12/2009 Libera et al.
2010/0095791 A1 4/2010 Galloway
2010/0132365 A1 6/2010 Labala
2010/0293961 A1 11/2010 Tong et al.
2010/0326085 A1 12/2010 Veilleux
2011/0077783 A1 3/2011 Karpman et al.
2011/0146276 A1 6/2011 Sathyanarayana et al.
2011/0153295 A1 6/2011 Yerramalla et al.
2011/0289936 A1 12/2011 Suciu et al.
2011/0296843 A1 12/2011 Lawson, Jr.
2011/0308345 A1 12/2011 Makulec et al.
2012/0031067 A1 2/2012 Sundaram et al.
2012/0121373 A1 5/2012 Short et al.
2012/0240591 A1 9/2012 Snider et al.
2012/0266601 A1 10/2012 Miller
2012/0297781 A1 11/2012 Manchikanti et al.
2012/0316748 A1 12/2012 Jegu et al.
2013/0031912 A1 2/2013 Finney et al.
2013/0091850 A1 4/2013 Francisco
2013/0101391 A1 4/2013 Szwedowicz et al.
2013/0134719 A1 5/2013 Watanabe et al.
2013/0251501 A1 9/2013 Araki et al.
2014/0060076 A1 3/2014 Cortelli et al.
2014/0123673 A1 5/2014 Mouze et al.
2014/0199157 A1 7/2014 Haerms et al.
2014/0236451 A1 8/2014 Gerez et al.
2014/0241878 A1 8/2014 Herrig et al.
2014/0271152 A1 9/2014 Rodriguez
2014/0301820 A1 10/2014 Lohse et al.
2014/0318144 A1 10/2014 Lazzeri et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2014/0321981	A1*	10/2014	Rodriguez	F01D 25/26 415/116
2014/0334927	A1	11/2014	Hammerum	
2014/0366546	A1	12/2014	Bruno et al.	
2014/0373518	A1	12/2014	Manneville et al.	
2014/0373552	A1*	12/2014	Zaccaria	F02C 7/277 60/778
2014/0373553	A1	12/2014	Zaccaria et al.	
2014/0373554	A1	12/2014	Pech et al.	
2015/0016949	A1	1/2015	Smith	
2015/0115608	A1	4/2015	Draper	
2015/0121874	A1	5/2015	Yoshida et al.	
2015/0128592	A1	5/2015	Filiputti et al.	
2015/0159625	A1	6/2015	Hawdwicke, Jr. et al.	
2015/0219121	A1	8/2015	King	
2015/0377141	A1	12/2015	Foiret	
2016/0236369	A1	8/2016	Baker	
2016/0245312	A1	8/2016	Morice	
2016/0265387	A1	9/2016	Duong et al.	
2016/0288325	A1	10/2016	Naderer et al.	
2017/0030265	A1	2/2017	O'Toole et al.	
2017/0218848	A1	8/2017	Alstad et al.	
2017/0233103	A1	8/2017	Teicholz et al.	
2017/0234158	A1	8/2017	Savela	
2017/0234166	A1	8/2017	Dube et al.	
2017/0234167	A1	8/2017	Stachowiak et al.	
2017/0234230	A1	8/2017	Schwarz et al.	
2017/0234231	A1	8/2017	Virtue, Jr. et al.	
2017/0234232	A1	8/2017	Sheridan et al.	
2017/0234233	A1	8/2017	Schwarz et al.	
2017/0234235	A1	8/2017	Pech	
2017/0234236	A1	8/2017	Feulner et al.	
2017/0234238	A1	8/2017	Schwarz et al.	
2017/0236064	A1	8/2017	Kirschnick	
2017/0274390	A1	9/2017	Manyapu et al.	
2018/0010480	A1	1/2018	Hockaday et al.	
2018/0265223	A1	9/2018	Teicholz et al.	
2018/0274390	A1	9/2018	Clauson et al.	
2018/0327117	A1	11/2018	Teicholz et al.	

FOREIGN PATENT DOCUMENTS

EP	1862875		12/2007
EP	2006496		12/2008
EP	2305986	A2	4/2011
EP	2363575	A2	9/2011
EP	2871333		5/2015
EP	3051074		8/2016
FR	2933131		1/2010
GB	1374810		11/1974
GB	2117842		10/1983
GB	2218751		11/1989
IN	201408865		5/2015
JP	2002371806		12/2002
JP	2004036414		2/2004
WO	9900585		1/1999
WO	2013007912		1/2013
WO	2014152701	A1	9/2014
WO	2015030946		3/2015
WO	2016069303		5/2016

OTHER PUBLICATIONS

EP Application No. 17155601 Extended European Search Report dated Jun. 30, 2017, 7 pages.

EP Application No. 17155612 Extended European Search Report dated Jul. 4, 2017, 8 pages.

EP Application No. 17155612.9 Office Action dated Oct. 2, 2018, 3 pages.

EP Application No. 17155613 Extended European Search Report dated Jun. 27, 2017, 10 pages.

EP Application No. 17155683 Extended European Search Report dated Jun. 30, 2017, 8 pages.

EP Application No. 17155683 Office Action dated May 22, 2018, 2 pages.

EP Application No. 17155687 Extended European Search Report dated Jun. 16, 2017, 9 pages.

EP Application No. 17155698 Extended European Search Report dated Jun. 21, 2017, 9 pages.

EP Application No. 17155698.8 Office Action dated Sep. 27, 2018, 3 pages.

EP Application No. 17155698.8 Office Action dated Jul. 17, 2019, 4 pages.

EP Application No. 17155721 Extended European Search Report dated Jun. 27, 2017, 8 pages.

EP Application No. 17155793 Extended European Search Report dated Jun. 30, 2017, 10 pages.

EP Application No. 17155798 Extended European Search Report dated Jun. 30, 2017, 9 pages.

EP Application No. 17155798.6 Office Action dated Sep. 21, 2018, 3 pages.

EP Application No. 17155807 Extended European Search Report dated Jul. 3, 2017, 8 pages.

Extended European Search Report for Application No. 17179407.6-1610 dated Dec. 5, 2017, 8 pages.

EP Application No. 20164205.5 Extended EP Search Report dated May 27, 2020, 8 pages.

EP Application No. 17155698.8 Office Action dated Apr. 22, 2021, 6 pages.

* cited by examiner

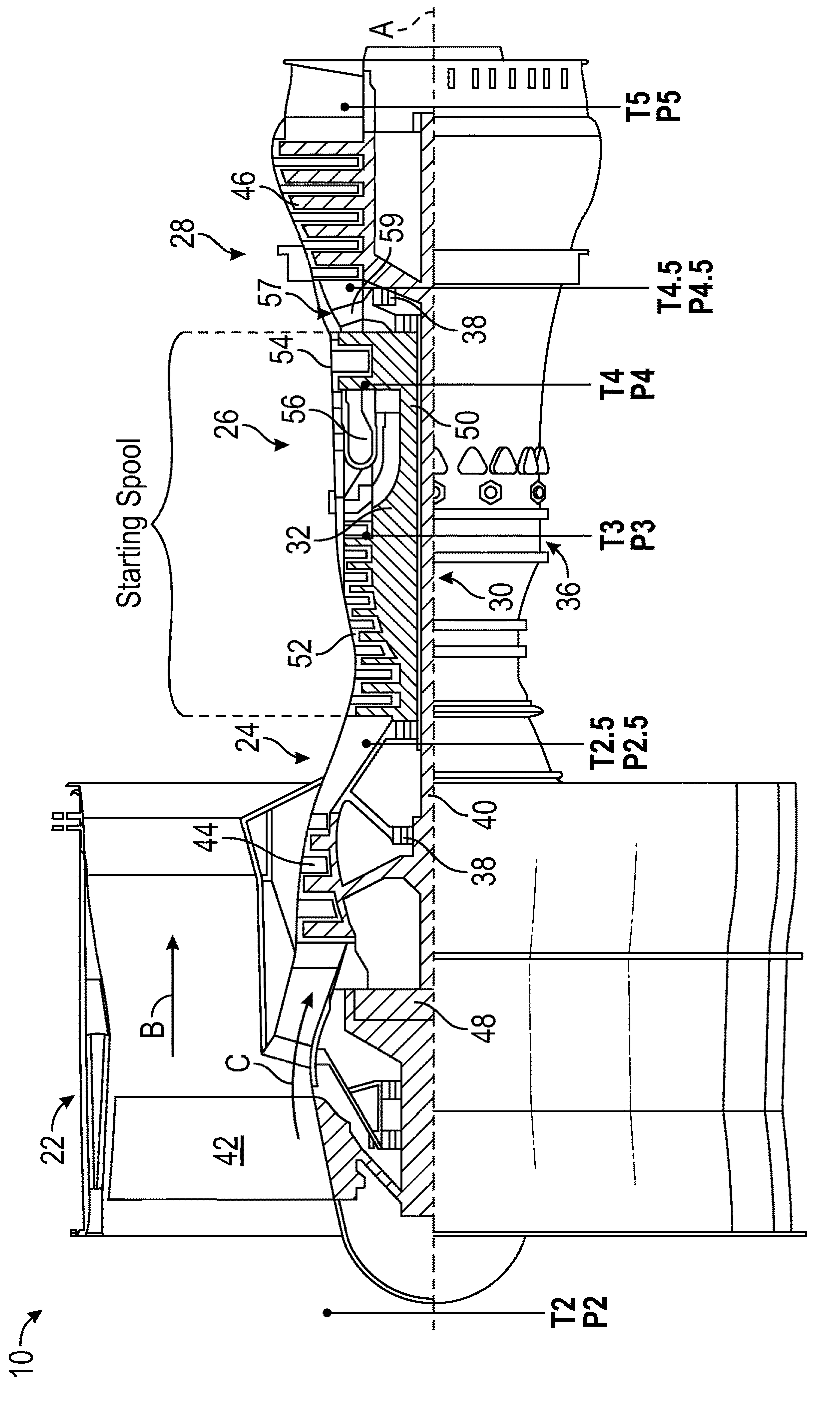

A
T5
P5
46
28
59
T4.5
P4.5
57
38
54
T4
P4
56
26
50
Starting Spool
32
T3
P3
30
36
52
24
T2.5
P2.5
40
44
38
B
C
48
22
42
T2
P2
10

FIG. 1

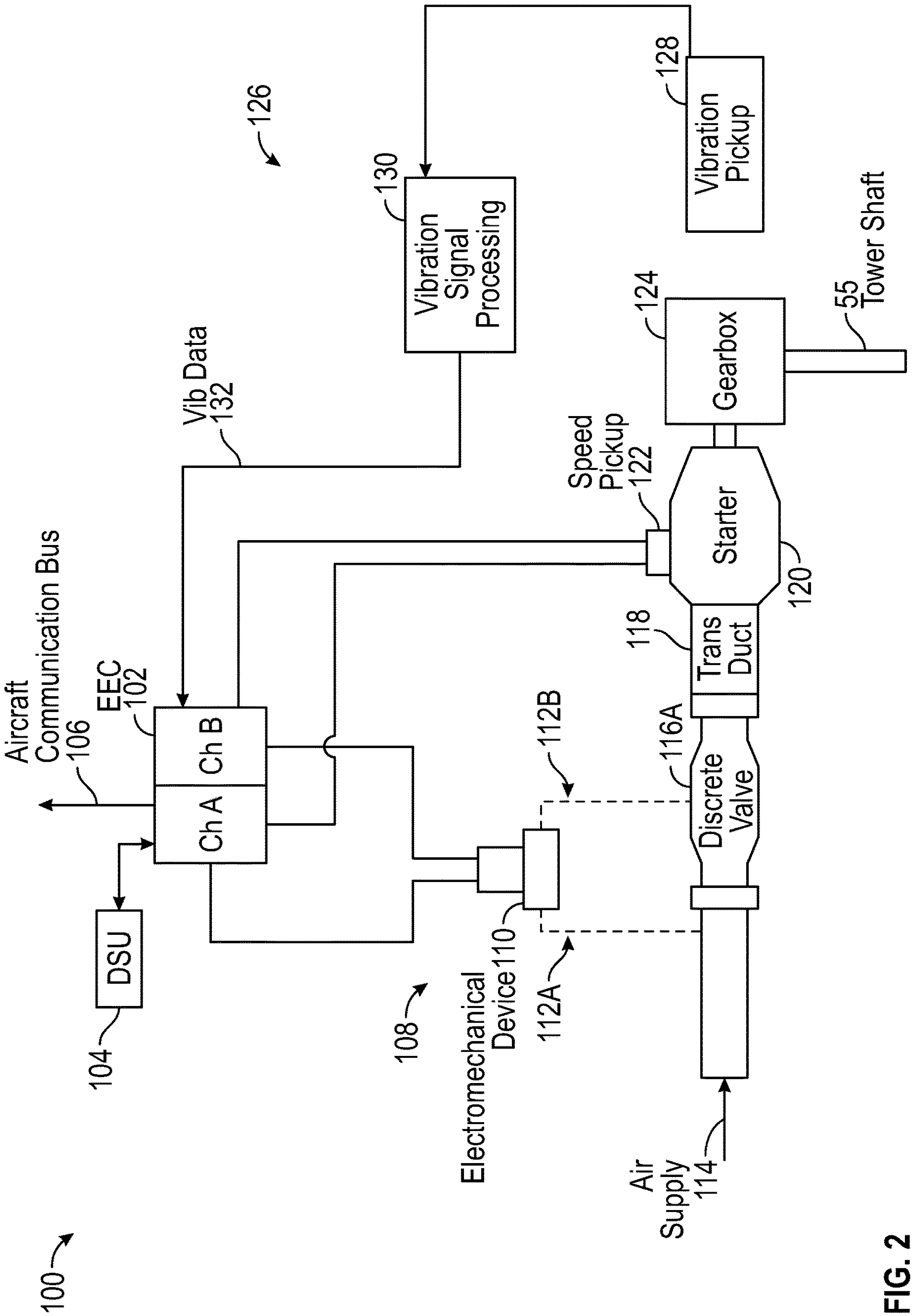

100
Aircraft Communication Bus 106
EEC 102
Ch A
Ch B
DSU
104
108
Electromechanical Device 110
112A
112B
Air Supply 114
Discrete Valve
116A
Trans Duct
118
Starter
120
Speed Pickup 122
Gearbox
124
55 Tower Shaft
Vib Data 132
Vibration Signal Processing
130
Vibration Pickup
128
126

FIG. 2

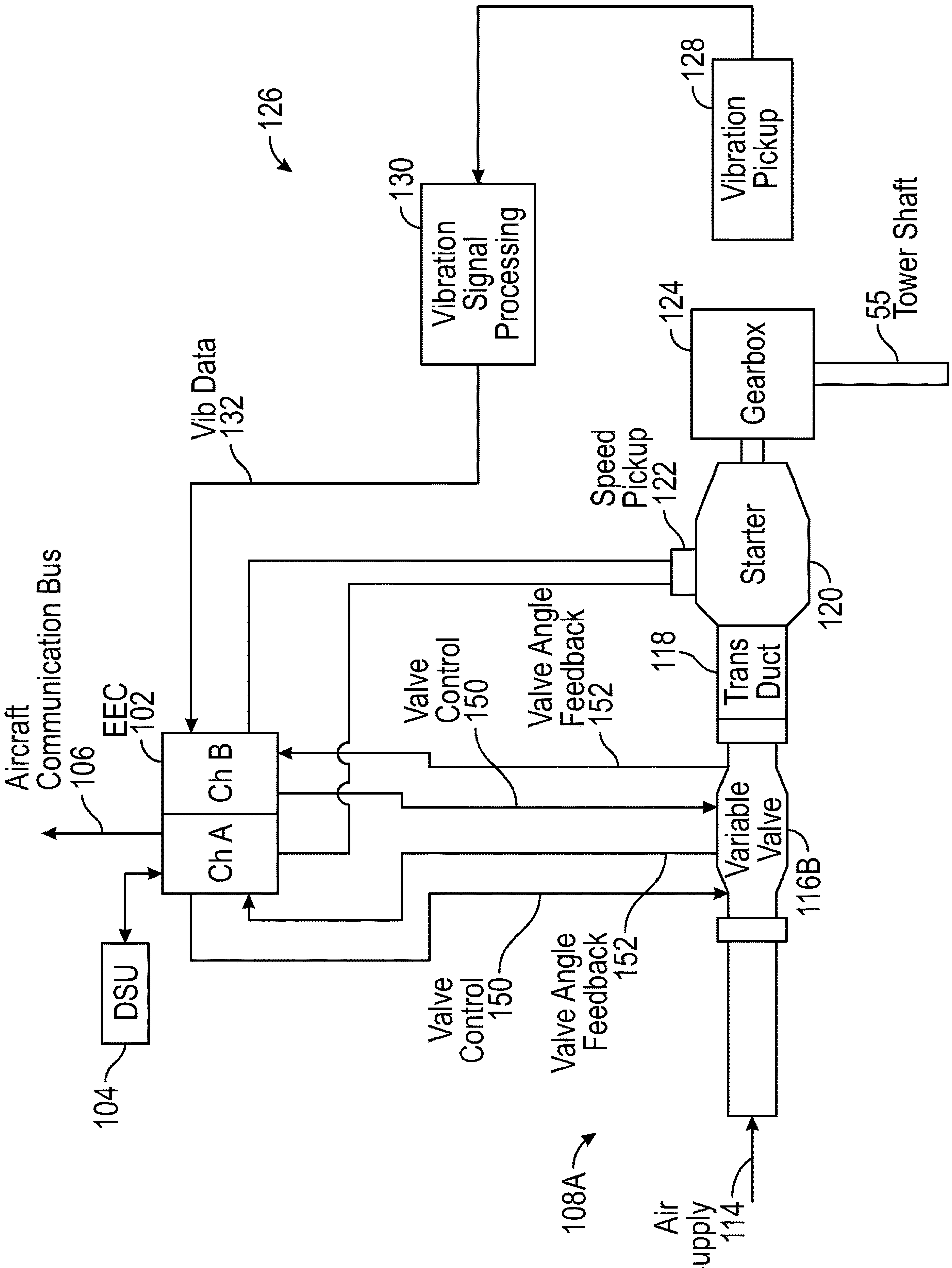

100A
Aircraft Communication Bus 106
EEC 102
Ch A
Ch B
DSU
104
Vib Data 132
126
Vibration Signal Processing
130
Vibration Pickup
128
Speed Pickup 122
Starter
120
Gearbox
124
55 Tower Shaft
Trans Duct
118
Variable Valve
116B
Valve Control 150
Valve Angle Feedback 152
Valve Control 150
Valve Angle Feedback 152
108A
Air Supply 114

FIG. 3

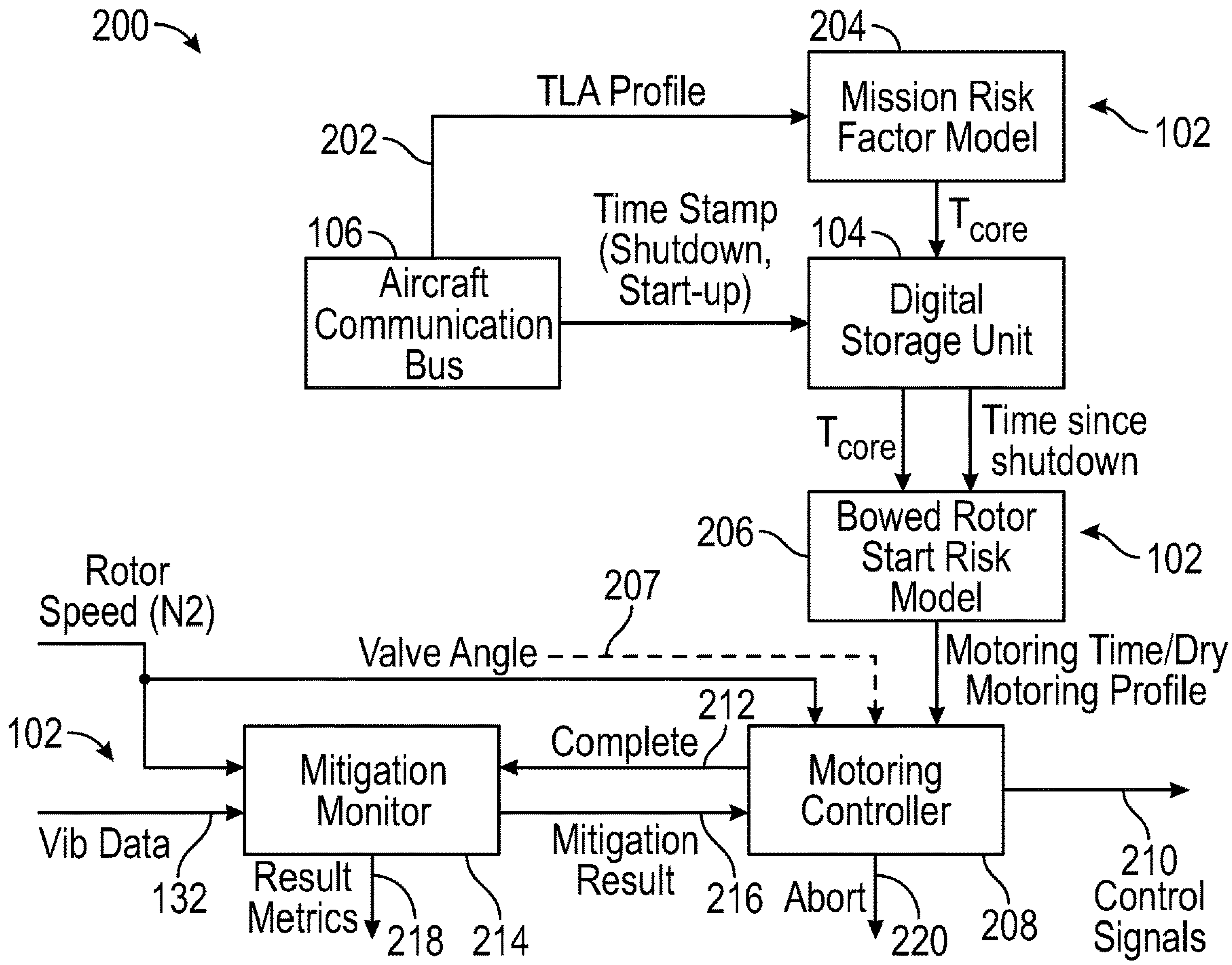

200
204
Mission Risk Factor Model
102
TLA Profile
202
106
Aircraft Communication Bus
Time Stamp (Shutdown, Start-up)
T_{core}
104
Digital Storage Unit
T_{core}
Time since shutdown
206
Bowed Rotor Start Risk Model
102
Rotor Speed (N2)
207
Valve Angle
Motoring Time/Dry Motoring Profile
102
212
Complete
Mitigation Monitor
Motoring Controller
Vib Data
132
Result Metrics
218
214
Mitigation Result
216
Abort
220
208
210
Control Signals

FIG. 4

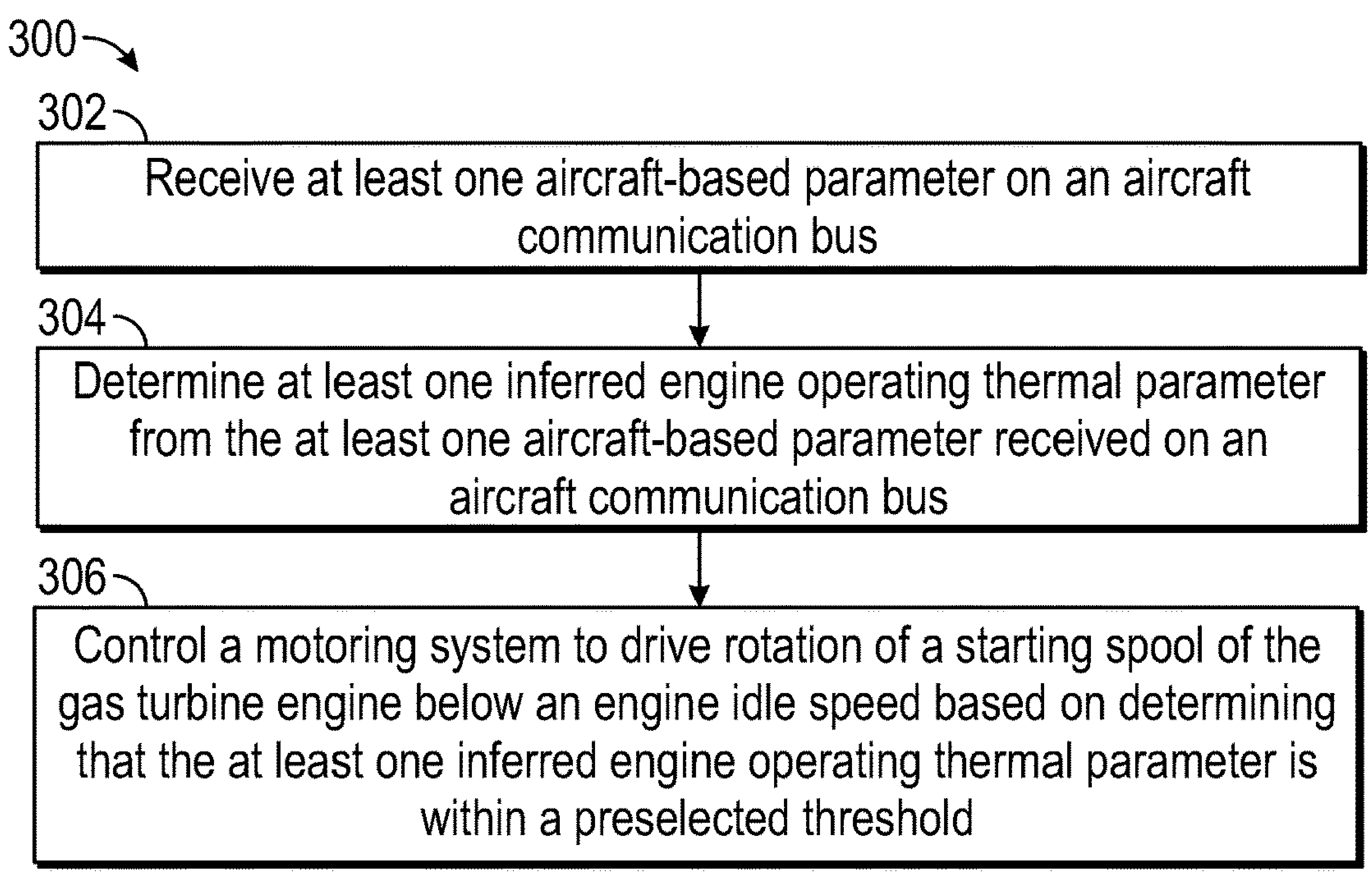
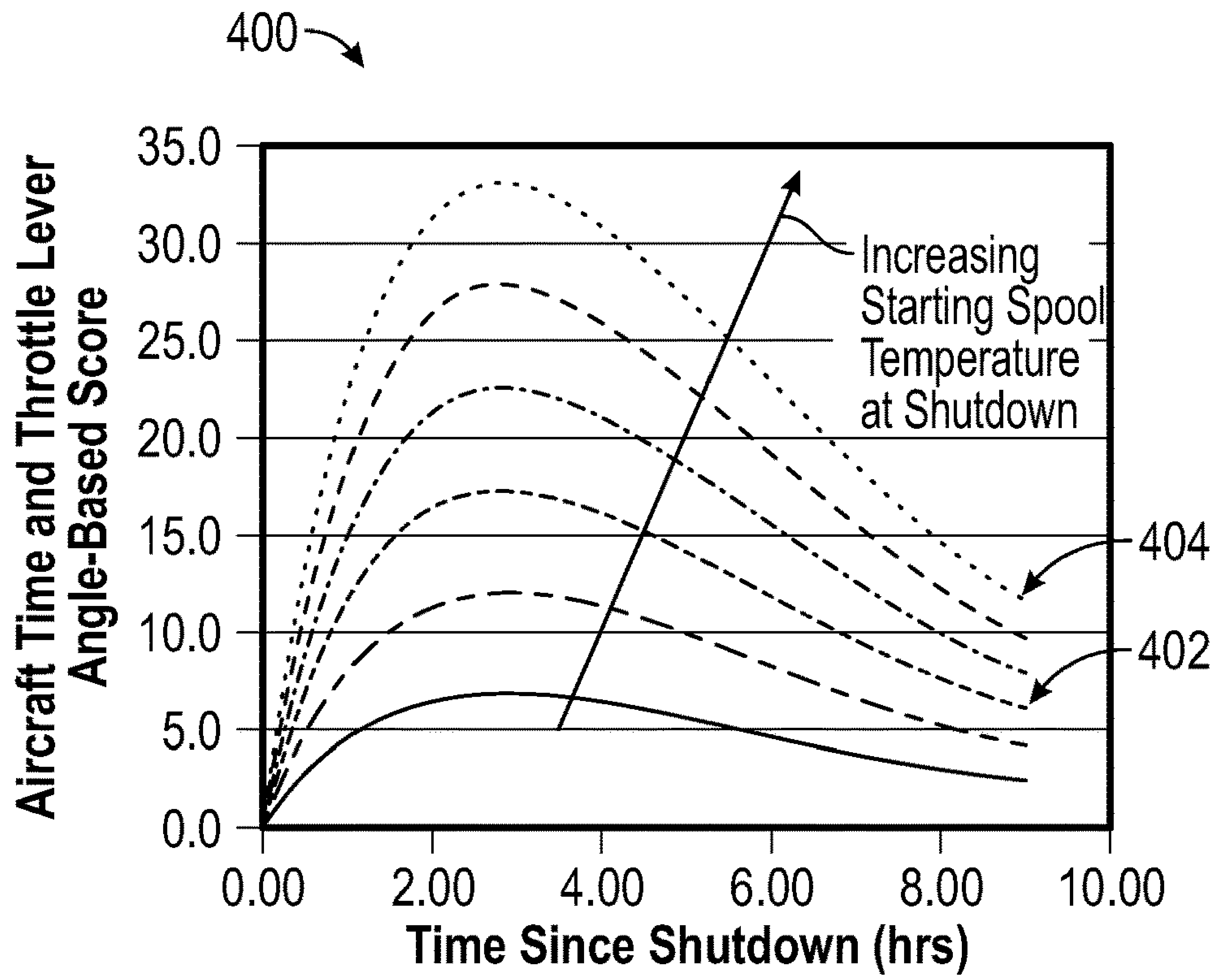
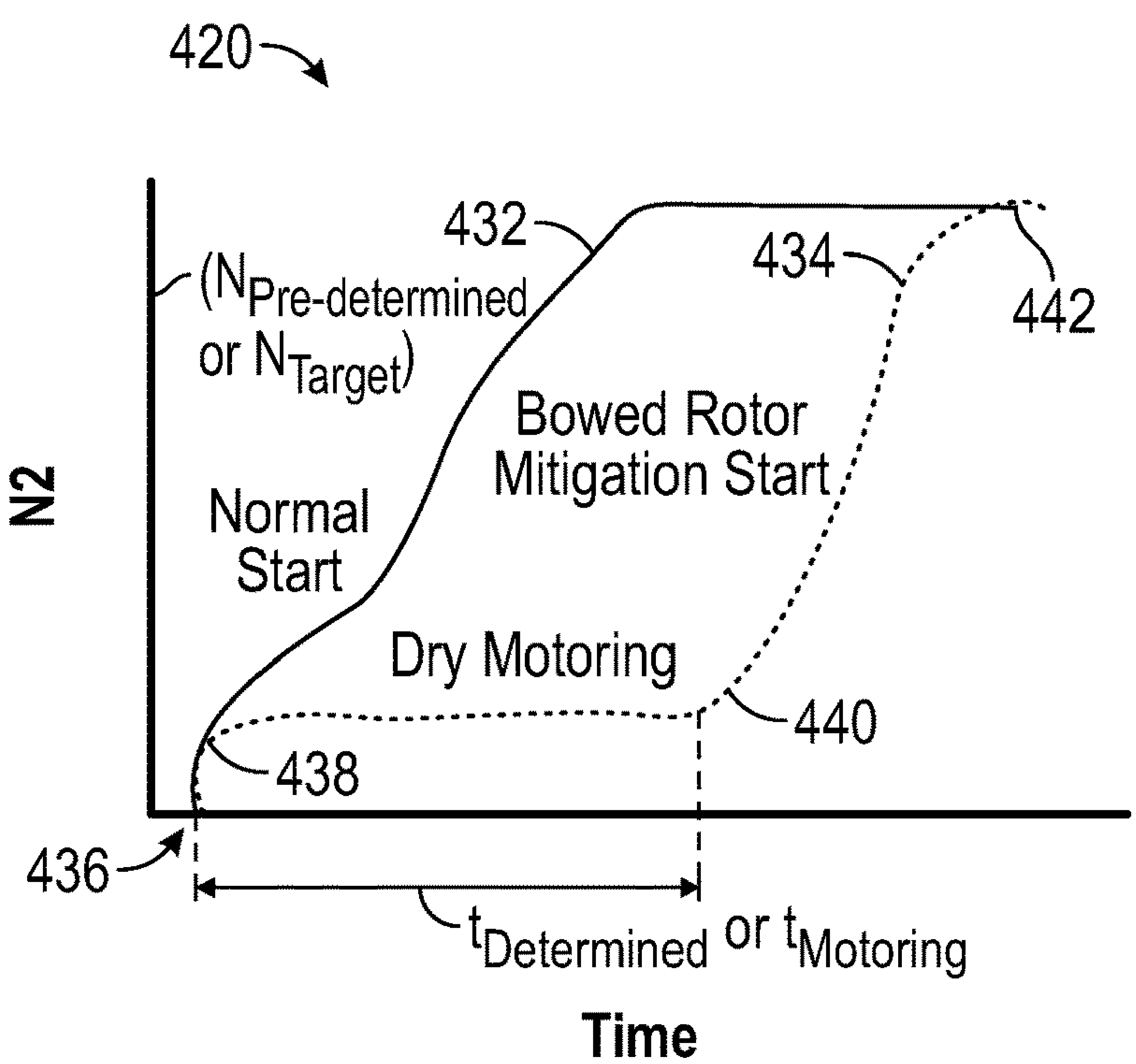

300
302
Receive at least one aircraft-based parameter on an aircraft communication bus
304
Determine at least one inferred engine operating thermal parameter from the at least one aircraft-based parameter received on an aircraft communication bus
306
Control a motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected threshold

FIG. 5



400
Aircraft Time and Throttle Lever Angle-Based Score
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.00
2.00
4.00
6.00
8.00
10.00
Time Since Shutdown (hrs)
Increasing Starting Spool Temperature at Shutdown
404
402

FIG. 6



420
N2
($N_{Pre\text{-}determined}$ or N_{Target})
432
434
442
Normal Start
Bowed Rotor Mitigation Start
Dry Motoring
438
440
436
$t_{Determined}$ or $t_{Motoring}$
Time

FIG. 7

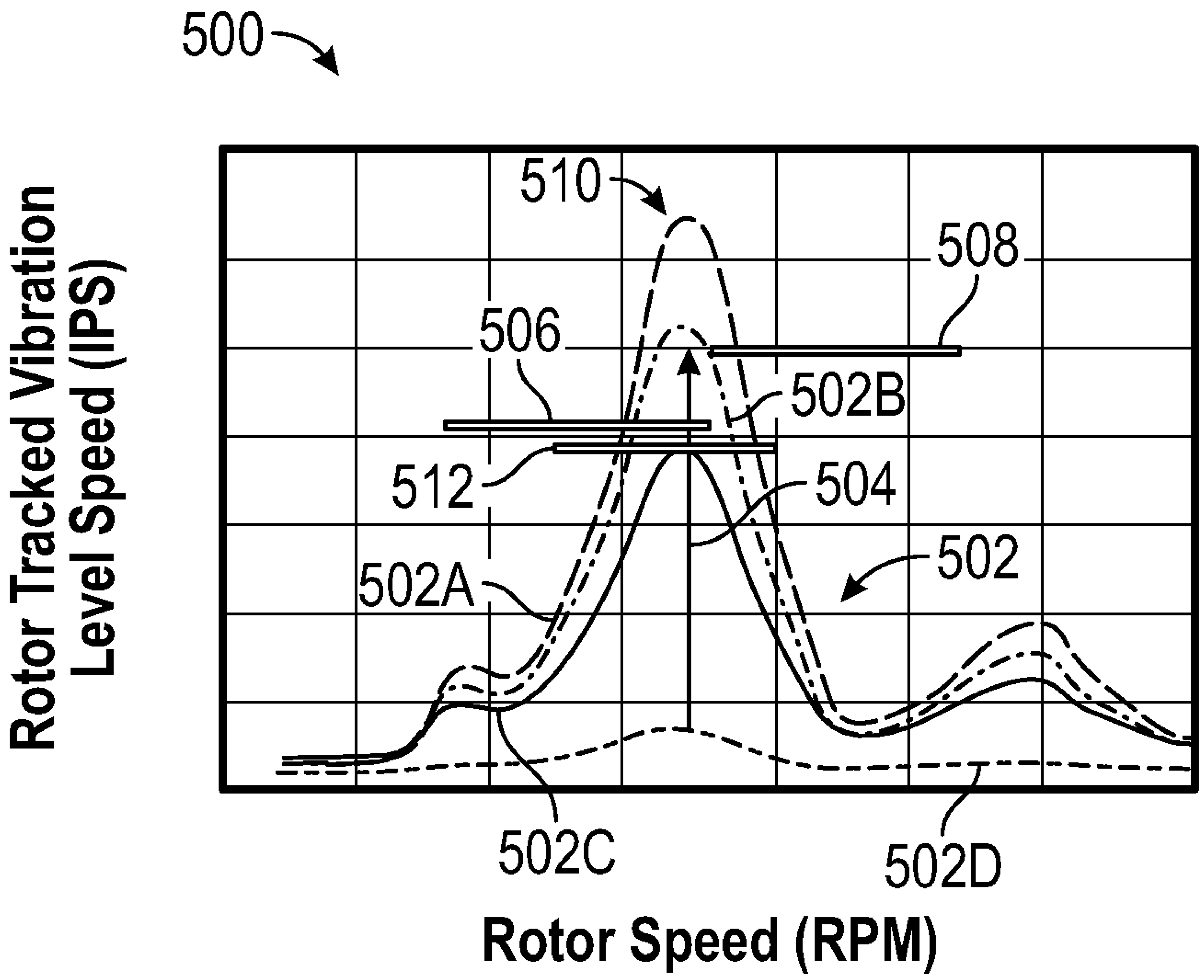

500
510
508
506
502B
512
504
502A
502
502C
502D
Rotor Tracked Vibration Level Speed (IPS)
Rotor Speed (RPM)

FIG. 8

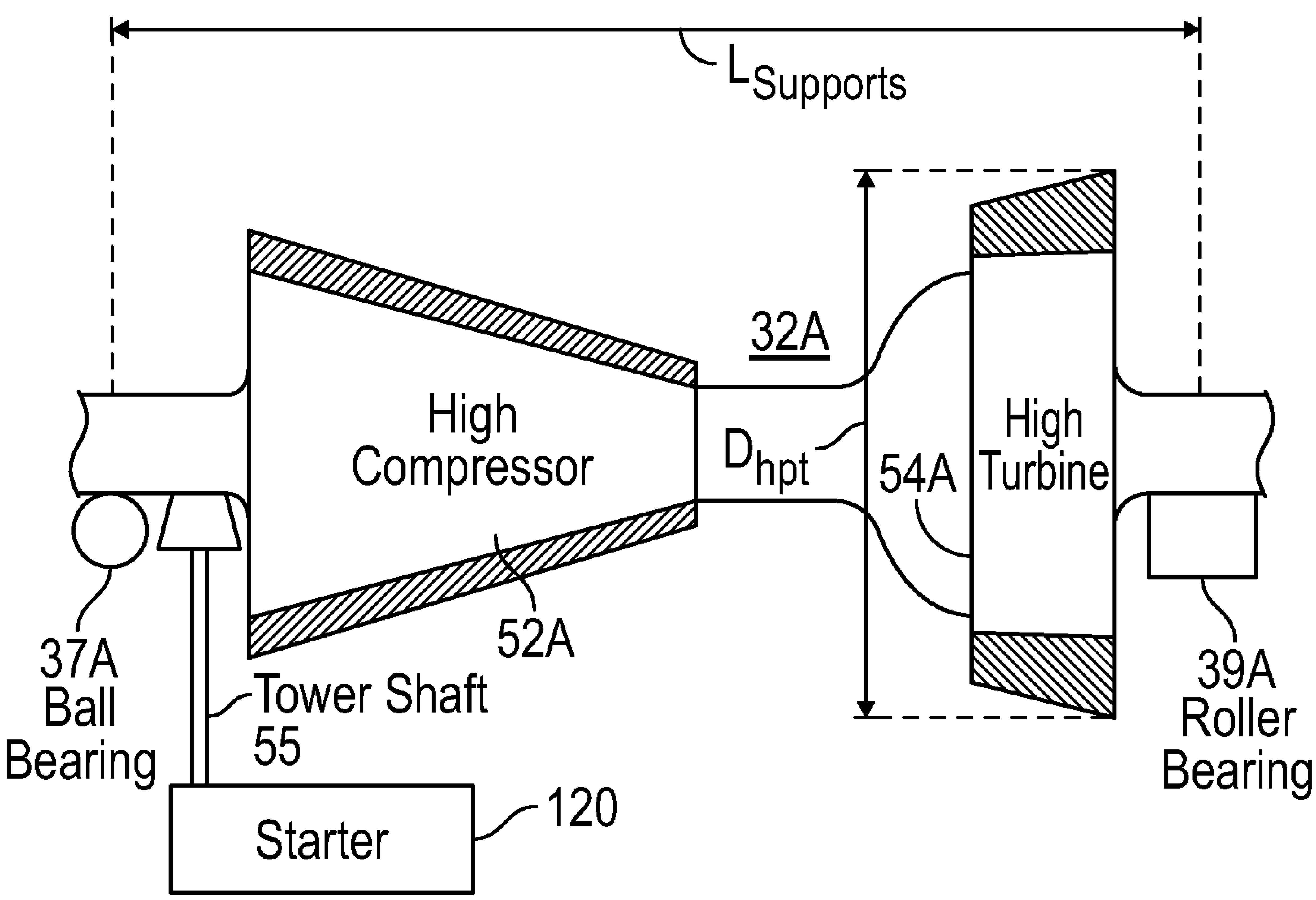

$L_{Supports}$
32A
High Compressor
D_{hpt}
54A
High Turbine
52A
37A Ball Bearing
Tower Shaft 55
Starter
120
39A Roller Bearing

FIG. 9

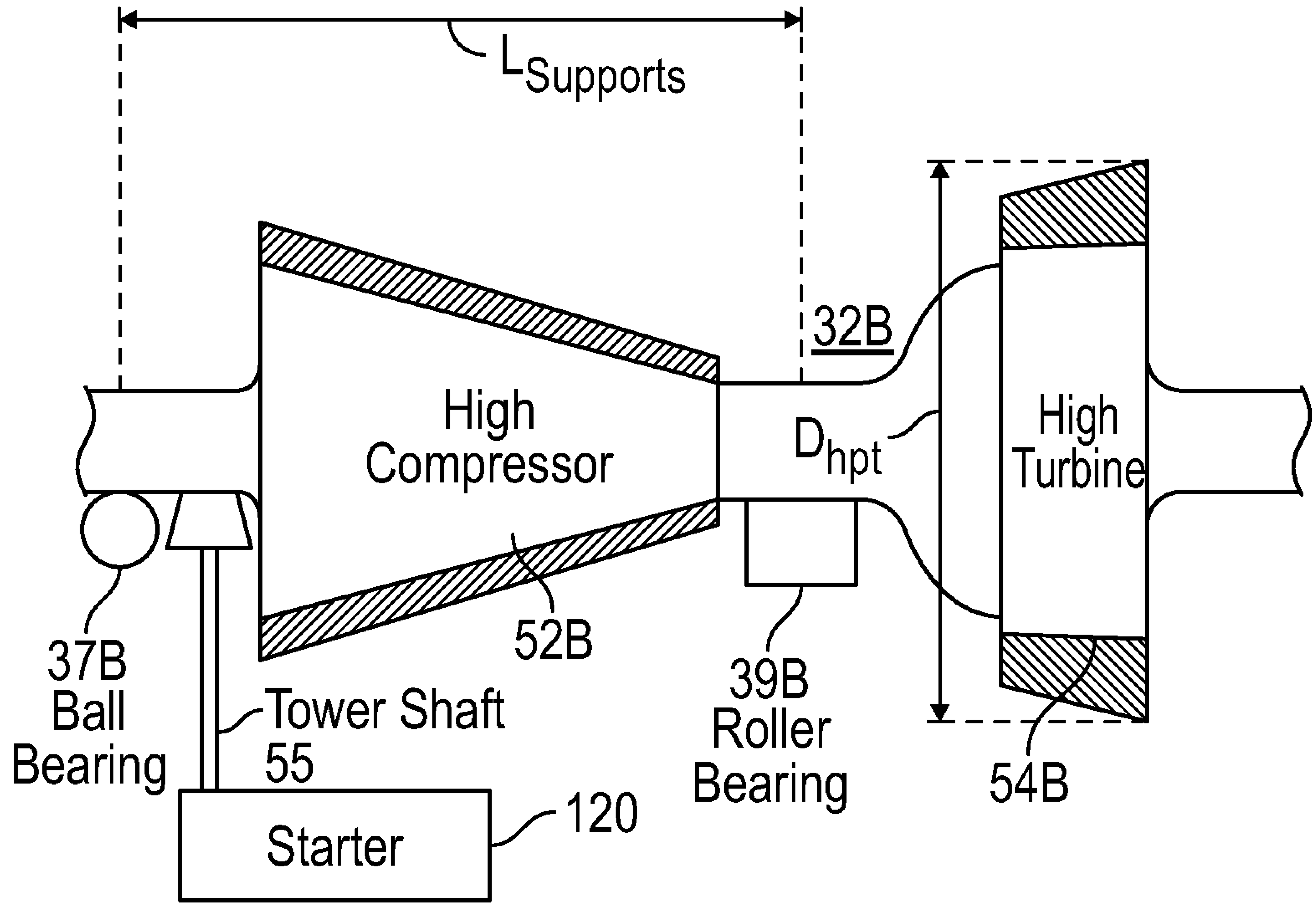

L Supports
32B
High Compressor
D hpt
High Turbine
37B Ball Bearing
Tower Shaft 55
52B
39B Roller Bearing
54B
Starter
120

FIG. 10

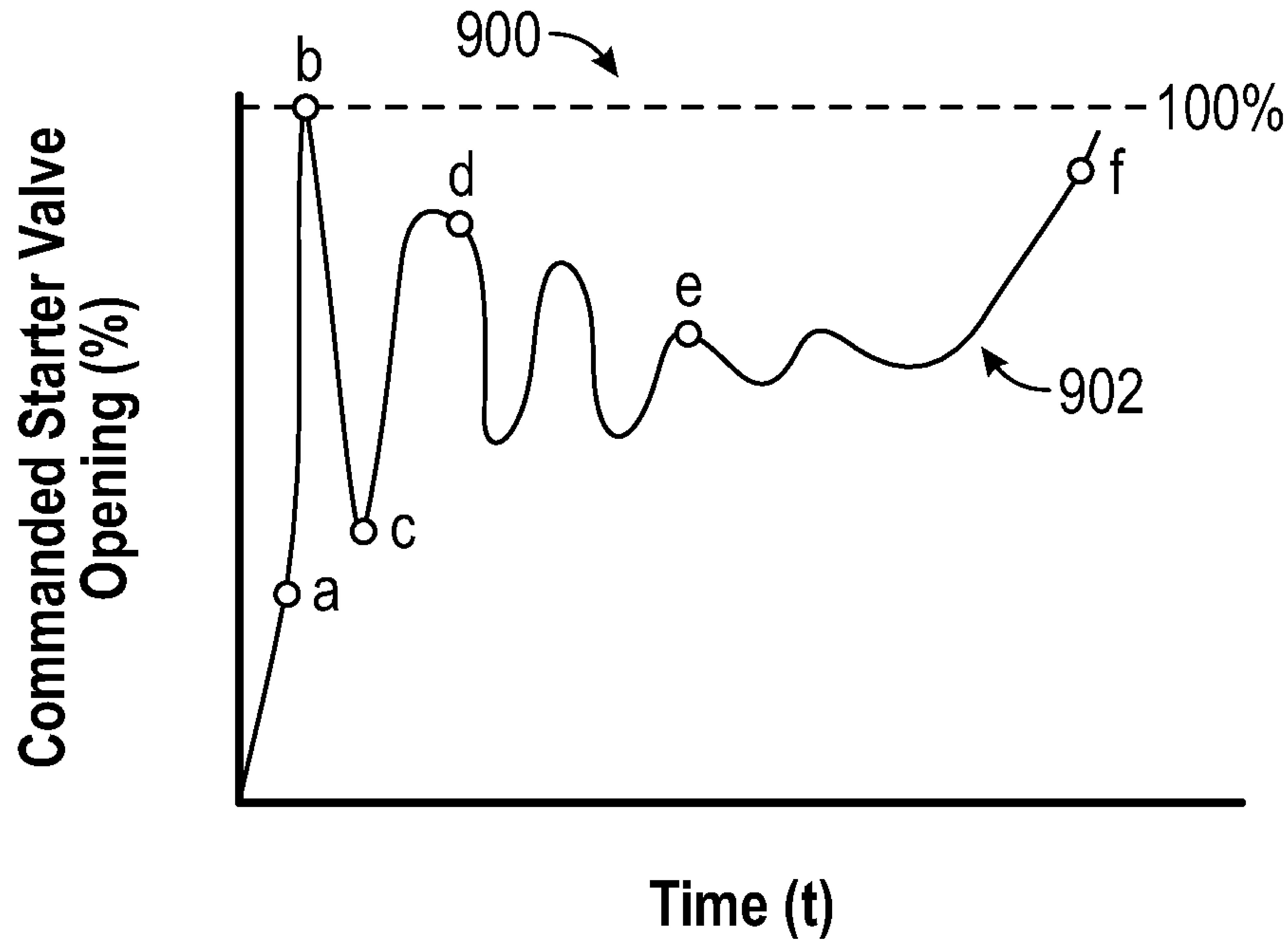

900
100%
b
d
e
f
a
c
902
Commanded Starter Valve Opening (%)
Time (t)

FIG. 11

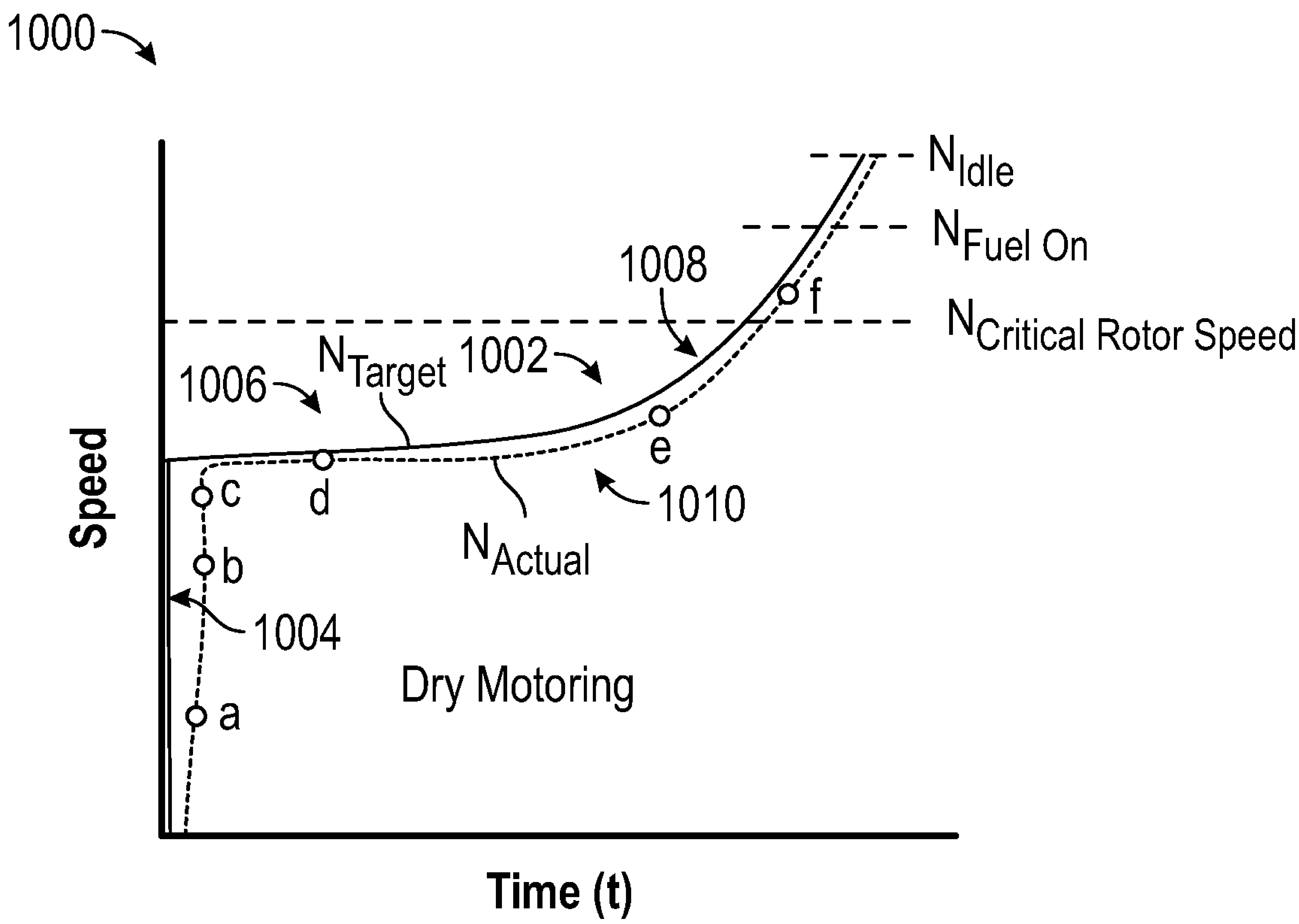

1000
NIdle
NFuel On
1008
f
NCritical Rotor Speed
NTarget
1002
1006
e
c
d
1010
Speed
NActual
b
1004
a
Dry Motoring
Time (t)

FIG. 12

BOWED ROTOR START MITIGATION IN A GAS TURBINE ENGINE USING AIRCRAFT-DERIVED PARAMETERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/042,724 filed Feb. 12, 2016, the disclosure of which is incorporated by reference herein in its entirety.

BACKGROUND

This disclosure relates to gas turbine engines, and more particularly to an apparatus, system and method for mitigating a bowed rotor start condition in a gas turbine engine using aircraft-derived parameters.

Gas turbine engines are used in numerous applications one of which is for providing thrust to an airplane. When the gas turbine engine of an airplane has been shut off for example, after an airplane has landed at an airport, the engine is hot and due to heat rise, the upper portions of the engine will be hotter than lower portions of the engine. When this occurs thermal expansion may cause deflection of components of the engine which may result in a "bowed rotor" condition. If a gas turbine engine is in such a "bowed rotor" condition it is undesirable to restart or start the engine.

Accordingly, it is desirable to provide a method and/or apparatus for detecting and preventing a "bowed rotor" condition.

BRIEF DESCRIPTION

In an embodiment, a bowed rotor start mitigation system for a gas turbine engine of an aircraft is provided. The bowed rotor start mitigation system includes a motoring system and a controller coupled to the motoring system and an aircraft communication bus. The controller is configured to determine at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The motoring system is controlled to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where a time since the engine shutdown is used to modify a time of rotation of the starting spool by the motoring system.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the controller transmits a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the controller is configured to abort rotation by the motoring system when a safety condition is detected.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the motoring system is configured to apply a braking torque to the starting spool to abort rotation of the starting spool.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include a rotation sensor for detecting rotary motion of the starting spool, and the controller is further coupled to the rotation sensor.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the controller is configured to remove power from the motoring system based on detecting rotary motion of the starting spool above a target speed.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where a vibration monitor is used to set a maintenance flag based on detecting a vibration level that exceeds a maintenance action threshold while accelerating the starting spool of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the at least one inferred engine operating thermal parameter includes an engine temperature value, and the at least one aircraft-based parameter received on the aircraft communication bus includes a throttle lever angle profile.

According to an embodiment, a method of bowed rotor start mitigation for a gas turbine engine of an aircraft is provided. The method includes determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on an aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The method also includes controlling a motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

A technical effect of the apparatus, systems and methods is achieved by using a start sequence for a gas turbine engine as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the present disclosure is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the present disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a cross-sectional view of a gas turbine engine;

FIG. **2** is a schematic illustration of a starting system for a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. **3** is a schematic illustration of a starting system for a gas turbine engine in accordance with another embodiment of the disclosure;

FIG. 4 is a block diagram of a system for bowed rotor start mitigation in accordance with an embodiment of the disclosure;

FIG. 5 is a flow chart illustrating a method of bowed rotor start mitigation of a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. 6 is a graph illustrating a bowed rotor risk score with respect to time in accordance with an embodiment of the disclosure;

FIG. 7 is a graph illustrating a normal or cooled engine start versus a modified engine start in accordance with an embodiment of the disclosure;

FIG. 8 is a graph illustrating examples of various vibration level profiles of an engine in accordance with an embodiment of the disclosure;

FIG. 9 is a schematic illustration of a high spool gas path with a straddle-mounted spool in accordance with an embodiment of the disclosure;

FIG. 10 is a schematic illustration of a high spool gas path with an overhung spool in accordance with an embodiment of the disclosure;

FIG. 11 is a graph illustrating commanded starter valve opening with respect to time in accordance with an embodiment of the disclosure; and

FIG. 12 is a graph illustrating a target rotor speed profile of a dry motoring profile and an actual rotor speed versus time in accordance with an embodiment of the disclosure.

DETAILED DESCRIPTION

Various embodiments of the present disclosure are related to a bowed rotor start mitigation system in a gas turbine engine. Embodiments can include a mission risk factor model used to estimate heat stored in an engine core at shutdown and identify a risk of a bowed rotor in the gas turbine engine based on one or more aircraft parameters. Information from the mission risk factor model can be used by a bowed rotor start risk model to calculate a bowed rotor risk parameter. As used herein the term "model" may be referred to in one non-limiting manner as a process for representing real world values, measurements or conditions through the use of a computer program or algorithm. The bowed rotor risk parameter may be used to take a control action to mitigate the risk of starting the gas turbine engine with a bowed rotor. The control action can include performing dry motoring as further described herein.

During dry motoring, a starter valve can be actively adjusted to deliver air pressure from an air supply to an engine starting system that controls starting rotor speed. Dry motoring may be performed by running an engine starting system at a lower speed with a longer duration than typically used for engine starting while dynamically adjusting the starter valve to maintain the rotor speed and/or follow a dry motoring profile. Some embodiments increase the rotor speed of the starting spool to approach a critical rotor speed gradually and as thermal distortion is decreased they then accelerate beyond the critical rotor speed to complete the engine starting process. The critical rotor speed refers to a major resonance speed where, if the temperatures are unhomogenized, the combination of a bowed rotor and similarly bowed casing and the resonance would lead to high amplitude oscillation in the rotor and high rubbing of blade tips on one side of the rotor, especially in the high pressure compressor if the rotor is straddle-mounted.

In some embodiments, a targeted rotor speed profile of the dry motoring profile can be adjusted as dry motoring is performed. As one example, if excessive vibration is detected as the rotor speed rises and approaches but remains well below the critical rotor speed, then the rate of rotor speed increases scheduled in the dry motoring profile can be reduced (i.e., a shallower slope) to extend the dry motoring time. Similarly, if vibration levels are observed below an expected minimum vibration level as the rotor speed increases, the dry motoring profile can be adjusted to a higher rate of rotor speed increases to reduce the dry motoring time.

A full authority digital engine control (FADEC) system or other system may send a message to the cockpit to extend time at idle to cool down the rotor prior to shut down. If the engine is in a ground test or in a test stand, a message can be sent to the test stand or cockpit based on the control-calculated risk of a bowed rotor. A test stand crew can be alerted regarding a requirement to bring the starting spool of the engine to a speed below the known resonance speed of the rotor in order to homogenize the temperature of the rotor and the casings about the rotor which also are distorted by temperature non-uniformity.

Monitoring of vibration signatures during the engine starting sequence can also or separately be used to assess the risk that a bowed rotor start has occurred due to some system malfunction and then direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor. Vibration data for the engine can also be monitored after bowed rotor mitigation is performed during an engine start sequence to confirm success of bowed rotor mitigation. If bowed rotor mitigation is unsuccessful or determined to be incomplete by the FADEC, resulting metrics (e.g., time, date, global positioning satellite (GPS) coordinates, vibration level vs. time, etc.) of the attempted bowed rotor mitigation can be recorded and/or transmitted to direct maintenance.

According to various embodiments, there are a number of options available to mitigate a bowed rotor start depending on a present operating state of the gas turbine engine, instrumentation, and monitoring systems implemented. For example, a control-calculated risk of a bowed rotor can be computed as a bowed rotor risk parameter as further described herein and used to trigger a cockpit message or test stand message to extend a time period to run at idle power prior to engine shutdown as a pre-shutdown mitigation. Alternatively, the bowed rotor risk parameter can trigger a request message or automated initiation of a dry motoring sequence prior to engine start. During a dry motoring sequence, a starter air pressure valve can be modulated to limit high rotor speed below high spool resonance speed and prevent rub during dry motoring operation. The bowed rotor risk parameter can also be used to limit dry motoring duration to reduce the impact on air starter turbine life. The monitoring of vibration signatures during the entire engine starting sequence can also or separately be used to assess the risk of a bowed rotor start and direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor.

Rather than using sensed parameters of an engine system, embodiments use parameters at the aircraft level, e.g., as received on an aircraft communication bus, to derive parameters at the engine level, such as engine core temperature. For example, a profile of a throttle lever angle (TLA) parameter history can indicate a history of fuel flow requested over a period of time which may be used to infer an engine core temperature. By determining an amount of elapsed time from the last received valid set of aircraft parameters in combination with a known engine state, e.g., engine shutdown, a minimum dry motoring time can be calculated.

Referring now to FIG. **1**, a schematic illustration of a gas turbine engine **10** is provided. The gas turbine engine **10** has among other components a fan through which ambient air is propelled into the engine housing, a compressor for pressurizing the air received from the fan and a combustor wherein the compressed air is mixed with fuel and ignited for generating combustion gases. The gas turbine engine **10** further comprises a turbine section for extracting energy from the combustion gases. Fuel is injected into the combustor of the gas turbine engine **10** for mixing with the compressed air from the compressor and ignition of the resultant mixture. The fan, compressor, combustor, and turbine are typically all concentric about a central longitudinal axis of the gas turbine engine **10**. Thus, thermal deflection of the components of the gas turbine engine **10** may create the aforementioned bowing or "bowed rotor" condition along the common central longitudinal axis of the gas turbine engine **10** and thus it is desirable to clear or remove the bowed condition prior to the starting or restarting of the gas turbine engine **10**.

FIG. **1** schematically illustrates a gas turbine engine **10** that can be used to power an aircraft, for example. The gas turbine engine **10** is disclosed herein as a multi-spool turbofan that generally incorporates a fan section **22**, a compressor section **24**, a combustor section **26** and a turbine section **28**. The fan section **22** drives air along a bypass flowpath while the compressor section **24** drives air along a core flowpath for compression and communication into the combustor section **26** then expansion through the turbine section **28**. Although depicted as a turbofan gas turbine engine in the disclosed non-limiting embodiment with two turbines and is sometimes referred to as a two spool engine, it should be understood that the concepts described herein are not limited to use with turbofans as the teachings may be applied to other types of turbine engines including three-spool architectures. In both of these architectures the starting spool is that spool that is located around the combustor, meaning the compressor part of the starting spool is flowing directly into the combustor and the combustor flows directly into the turbine section.

The engine **10** generally includes a low speed spool **30** and a high speed spool **32** mounted for rotation about an engine central longitudinal axis A relative to an engine static structure **36** via several bearing systems **38**. It should be understood that various bearing systems **38** at various locations may alternatively or additionally be provided.

The low speed spool **30** generally includes an inner shaft **40** that interconnects a fan **42**, a low pressure compressor **44** and a low pressure turbine **46**. The inner shaft **40** is connected to the fan **42** through a geared architecture **48** to drive the fan **42** at a lower speed than the low speed spool **30** in the example of FIG. **1**. The high speed spool **32** includes an outer shaft **50** that interconnects a high pressure compressor **52** and high pressure turbine **54**. A combustor **56** is arranged between the high pressure compressor **52** and the high pressure turbine **54**. A mid-turbine frame **57** of the engine static structure **36** is arranged generally between the high pressure turbine **54** and the low pressure turbine **46**. The mid-turbine frame **57** further supports bearing systems **38** in the turbine section **28**. The inner shaft **40** and the outer shaft **50** are concentric and rotate via bearing systems **38** about the engine central longitudinal axis A which is collinear with their longitudinal axes.

The core airflow is compressed by the low pressure compressor **44** then the high pressure compressor **52**, mixed and burned with fuel in the combustor **56**, then expanded over the high pressure turbine **54** and low pressure turbine **46**. The mid-turbine frame **57** includes airfoils **59** which are in the core airflow path. The turbines **46**, **54** rotationally drive the respective low speed spool **30** and high speed spool **32** in response to the expansion.

A number of stations for temperature and pressure are defined with respect to the gas turbine engine **10** according to conventional nomenclature. Station **2** is at an inlet of low pressure compressor **44** having a temperature T**2** and a pressure P**2**. Station **2.5** is at an exit of the low pressure compressor **44** having a temperature T**2.5** and a pressure P**2.5**. Station **3** is at an inlet of the combustor **56** having a temperature T**3** and a pressure P**3**. Station **4** is at an exit of the combustor **56** having a temperature T**4** and a pressure P**4**. Station **4.5** is at an exit of the high pressure turbine **54** having a temperature T**4.5** and a pressure P**4.5**. Station **5** is at an exit of the low pressure turbine **46** having a temperature T**5** and a pressure P**5**. Embodiments use aircraft-derived parameters rather than measured parameters at the stations depicted in FIG. **1** for bowed rotor mitigation.

Although FIG. **1** depicts one example configuration, it will be understood that embodiments as described herein can cover a wide range of configurations. For example, embodiments may be implemented in a configuration that is described as a "straddle-mounted" spool **32**A of FIG. **9**. This configuration places two bearing compartments **37**A and **39**A (which may include a ball bearing and a roller bearing respectively), outside of the plane of most of the compressor disks of high pressure compressor **52**A and at outside at least one of the turbine disks of high pressure turbine **54**A. In contrast with a straddle-mounted spool arrangement, other embodiments may be implemented using an over-hung mounted spool **32**B as depicted in FIG. **10**. In over-hung mounted spool **32**B, a bearing compartment **37**B is located forward of the first turbine disk of high pressure turbine **54**B such that the high pressure turbine **54**B is overhung, and it is physically located aft of its main supporting structure. The use of straddle-mounted spools has advantages and disadvantages in the design of a gas turbine, but one characteristic of the straddle-mounted design is that the span between the bearing compartments **37**A and **39**A is long, making the amplitude of the high spot of a bowed rotor greater and the resonance speed that cannot be transited prior to temperature homogenization is lower. For any thrust rating, the straddle mounted arrangement, such as straddle-mounted spool **32**A, gives Lsupport/Dhpt values that are higher, and the overhung mounted arrangement, such as overhung spool **32**B, can be as much as 60% of the straddle-mounted Lsupport/Dhpt. Lsupport is the distance between bearings (e.g., between bearing compartments **37**A and **39**A or between bearing compartments **37**B and **39**B), and Dhpt is the diameter of the last blade of the high pressure turbine (e.g., high pressure turbine **54**A or high pressure turbine **54**B). As one example, a straddle-mounted engine starting spool, such as straddle-mounted spool **32**A, with a roller bearing at bearing compartment **39**A located aft of the high pressure turbine **54**A may be more vulnerable to bowed rotor problems since the Lsupport/Dhpt ranges from 1.9 to 5.6. FIGS. **9** and **10** also illustrate a starter **120** interfacing via a tower shaft **55** with the straddle-mounted spool **32**A proximate high compressor **52**A and interfacing via tower shaft **55** with the overhung mounted spool **32**B proximate high compressor **52**B as part of a starting system.

Turning now to FIG. **2**, a schematic of a starting system **100** for the gas turbine engine **10** of FIG. **1** is depicted according to an embodiment. The starting system **100** is also referred to generally as a gas turbine engine system. In the example of FIG. **2**, the starting system **100** includes a controller **102** which may be an electronic engine control, such as a dual-channel FADEC, and/or engine health monitoring unit. In an embodiment, the controller **102** may include memory to store instructions that are executed by one or more processors. The executable instructions may be stored or organized in any manner and at any level of abstraction, such as in connection with a controlling and/or monitoring operation of the engine **10** of FIG. **1**. The one or more processors can be any type of central processing unit (CPU), including a general purpose processor, a digital signal processor (DSP), a microcontroller, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or the like. Also, in embodiments, the memory may include random access memory (RAM), read only memory (ROM), or other electronic, optical, magnetic, or any other computer readable medium onto which is stored data and control algorithms in a non-transitory form.

The starting system **100** can also include a data storage unit (DSU) **104** that retains data between shutdowns of the gas turbine engine **10** of FIG. **1**. The DSU **104** includes non-volatile memory and retains data between cycling of power to the controller **102** and DSU **104**. An aircraft communication bus **106** can include an aircraft-level and/or test stand communication bus to interface with aircraft controls, e.g., a cockpit, various onboard computer systems, and/or a test stand. Based on detecting a bowed rotor start risk, the controller **102** can send a request for extended idle operation on the aircraft communication bus **106** prior to engine shutdown. Alternatively, the controller **102** can receive a request to initiate bowed rotor mitigation on the aircraft communication bus **106**.

A motoring system **108** is operable to drive rotation of a starting spool (e.g., high speed spool **32**) of the gas turbine engine **10** of FIG. **1**. Either or both channels of controller **102** can alternate on and off commands to an electromechanical device **110** coupled to a discrete starter valve **116**A to achieve a partially open position of the discrete starter valve **116**A to control a flow from a starter air supply **114** (also referred to as air supply **114**) through a transfer duct **118** to an air turbine starter **120** (also referred to as starter **120** or pneumatic starter motor **120**) to drive rotation of a starting spool of the gas turbine engine **10** below an engine idle speed. The air supply **114** (also referred to as starter air supply **114**) can be provided by any known source of compressed air, such as an auxiliary power unit or ground cart.

The controller **102** can monitor a speed sensor, such as speed pickup **122** that may sense the speed of the engine rotor through its connection to a gearbox **124** which is in turn connected to the high speed spool **32** via tower shaft **55** (e.g., rotational speed of high speed spool **32**) or any other such sensor for detecting or determining the speed of the gas turbine engine **10** of FIG. **1**. The starter **120** may be coupled to the gearbox **124** of the gas turbine engine **10** of FIG. **1** directly or through a transmission such as a clutch system (not depicted). The controller **102** can establish a control loop with respect to rotor speed to adjust positioning of the discrete starter valve **116**A.

The discrete starter valve **116**A is an embodiment of a starter valve that is designed as an on/off valve which is typically commanded to either fully opened or fully closed. However, there is a time lag to achieve the fully open position and the fully closed position. By selectively alternating an on-command time with an off-command time through the electromechanical device **110**, intermediate positioning states (i.e., partially opened/closed) can be achieved. The controller **102** can modulate the on and off commands (e.g., as a duty cycle using pulse width modulation) to the electromechanical device **110** to further open the discrete starter valve **116**A and increase a rotational speed of the starting spool of the gas turbine engine **10** of FIG. **1**. In an embodiment, the electromechanical device **110** has a cycle time defined between an off-command to an on-command to the off-command that is at least half of a movement time for the discrete starter valve **116**A to transition from fully closed to fully open. Pneumatic lines **112**A and **112**B or a mechanical linkage (not depicted) can be used to drive the discrete starter valve **116**A between the open position and the closed position. The electromechanical device **110** can be a solenoid that positions the discrete starter valve **116**A based on intermittently supplied electric power as commanded by the controller **102**. In an alternate embodiment, the electromechanical device **110** is an electric valve controlling muscle air to adjust the position of the discrete starter valve **116**A as commanded by the controller **102**.

In the example of FIG. **2**, the engine also includes a vibration monitoring system **126**. The vibration monitoring system **126** includes at least one vibration pickup **128**, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine **10** of FIG. **1**. Vibration signal processing **130** can be performed locally with respect to the vibration pickup **128**, within the controller **102**, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data **132**. Alternatively, the vibration monitoring system **126** can be omitted in some embodiments.

Similar to FIG. **2**, FIG. **3** is a schematic illustration of a starting system **100**A for the gas turbine engine **10** of FIG. **1** in accordance with another embodiment. The starting system **100**A includes controller **102** that controls motoring system **108**A, as an alternate embodiment of the motoring system **108** of FIG. **2**. Rather than using an electromechanical device **110** coupled to a discrete starter valve **116**A to achieve a partially open position of the discrete starter valve **116**A of FIG. **2**, the motoring system **108**A of FIG. **3** uses a variable position starter valve **116**B. In FIG. **3**, either or both channels of controller **102** can output a valve control signal **150** operable to dynamically adjust a valve angle of the variable position starter valve **116**A that selectively allows a portion of the air supply **114** to pass through the variable position starter valve **116**B and transfer duct **118** to air turbine starter **120**. The variable position starter valve **116**B is a continuous/infinitely adjustable valve that can hold a commanded valve angle, which may be expressed in terms of a percentage open/closed and/or an angular value (e.g., degrees or radians). Performance parameters of the variable position starter valve **116**B can be selected to meet dynamic response requirements of the starting system **100**A. For example, in some embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 40 seconds. In other embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 30 seconds. In further embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 20 seconds.

The controller **102** can monitor a valve angle of the variable position starter valve **116**B using valve angle feedback signals **152** provided to both channels of controller

102. As one example, in an active/standby configuration, both channels of the controller **102** can use the valve angle feedback signals **152** to track a current valve angle, while only one channel designated as an active channel outputs valve control signal **150**. Upon a failure of the active channel, the standby channel of controller **102** can take over as the active channel to output valve control signal **150**. In an alternate embodiment, both channels of controller **102** output all or a portion of a valve angle command simultaneously on the valve control signals **150**. The controller **102** can establish an outer control loop with respect to rotor speed and an inner control loop with respect to the valve angle of the variable position starter valve **116**B.

As in the example of FIG. **2**, the starting system **100**A of FIG. **3** also includes vibration monitoring system **126**. The vibration monitoring system **126** includes at least one vibration pickup **128**, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine **10** of FIG. **1**. Vibration signal processing **130** can be performed locally with respect to the vibration pickup **128**, within the controller **102**, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data **132**. Alternatively, the vibration monitoring system **126** can be omitted in some embodiments.

FIG. **4** is a block diagram of a system **200** for bowed rotor start mitigation that may control the discrete starter valve **116**A of FIG. **2** or the variable position starter valve **116**B of FIG. **3** via control signals **210** in accordance with an embodiment. The system **200** may also be referred to as a bowed rotor start mitigation system. In the example of FIG. **3**, the system **200** includes a mission risk factor model **204** which may be part of controller **102**.

The mission risk factor model **204** determines at least one inferred engine operating thermal parameter, such as an engine temperature value or heat state (T_{core}) of the gas turbine engine **10**, based on at least one aircraft-based parameter **202** received on the aircraft communication bus **106**. The at least one aircraft-based parameter **202** is an aircraft-level parameter which is not directly observable by engine system sensors coupled to the controller **102**. As one example, the at least one aircraft-based parameter **202** can be a throttle lever angle (TLA) profile indicate of a history of fuel demand for the aircraft. By observing the at least one aircraft-based parameter **202** over a period of time, the mission risk factor model can infer an engine operating thermal parameter, such as T_{core}. For instance, T_{core} can be determined by relating flight profile information, e.g., altitude, thrust demand, time, etc., with known performance characteristics of the gas turbine engine **10** of FIG. **1** using a series of computations and/or look-up table(s) stored in memory of controller **102**. The heat state of the engine **10** during use or T_{core} is inferred by the mission risk factor model **204** as the engine **10** is being run and valid instances of at least one aircraft-based parameter **202** are received on the aircraft communication bus **106**. The mission risk factor model **204** can infer T_{core} absent sensed values at the engine level.

At engine shutdown, the current or most recently determined heat state of the engine or T_{core} shutdown of the engine **10** is recorded into DSU **104**, and the time of the engine shutdown $t_{shutdown}$ is recorded into the DSU **104**. Time values and other parameters may be received on aircraft communication bus **106**.

During an engine start sequence or restart sequence, a bowed rotor start risk model **206** of the controller **102** is provided with the data stored in the DSU **104**, namely $T_{core\ shutdown}$ and the time of the engine shutdown $t_{shutdown}$. In addition, the bowed rotor start risk model **206** is also provided with the time of engine start t_{start}. Although the mission risk factor model **204** and the bowed rotor start risk model **206** are separately depicted, it will be understood that the mission risk factor model **204** and the bowed rotor start risk model **206** may be combined as a single model.

The bowed rotor start risk model **206** maps core temperature model data inferred from the at least one aircraft-based parameter **202** with time data to establish a motoring time $t_{motoring}$ as an estimated period of motoring to mitigate a bowed rotor of the gas turbine engine **10**. The motoring time $t_{motoring}$ is indicative of a bowed rotor risk parameter computed by the bowed rotor start risk model **206**. The bowed rotor risk parameter may be quantified according to a profile curve **402** selected from a family of curves **404** that align with observed aircraft conditions, such as a longer duration of a higher TLA value, which increases turbine bore temperature and the resulting bowed rotor risk as depicted in the example graph **400** of FIG. **6**. For instance, a higher risk of a bowed rotor may result in a longer duration of dry motoring to reduce a temperature gradient prior to starting the gas turbine engine **10** of FIG. **1**. As will be discussed herein and in one embodiment, an engine start sequence may automatically include a modified start sequence; however, the duration of the modified start sequence prior to a normal start sequence will vary based upon the time period $t_{motoring}$ that is calculated by the bowed rotor start risk model **206**. The motoring time $t_{motoring}$ for predetermined target speed N_{target} of the engine **10** can be calculated as a function of $T_{core\ shutdown}$, $t_{shutdown}$, and t_{start}, (e.g., f ($T_{core\ shutdown}$, $t_{shutdown}$, and t_{start}), while a target speed N_{target} is a predetermined speed that can be fixed or vary within a predetermined speed range of $N_{targetMin}$ to $N_{targetMax}$. In other words, the target speed N_{target} can be the same regardless of the calculated time period $t_{motoring}$ or may vary within the predetermined speed range of $N_{targetMin}$ to $N_{targetMax}$. The target speed N_{target} may also be referred to as a dry motoring mode speed.

Based upon these values ($T_{core\ shutdown}$, $t_{shutdown}$, and t_{start}) the motoring time $t_{motoring}$ at a predetermined target speed N_{target} for the modified start sequence of the engine **10** is determined by the bowed rotor start risk model **206**. Based upon the calculated time period $t_{motoring}$ which is calculated as a time to run the engine **10** at a predetermined target speed N_{target} in order to clear a "bowed condition". In accordance with an embodiment of the disclosure, the controller **102** can run through a modified start sequence upon a start command given to the engine **10** by an operator of the engine **10** such as a pilot of an airplane the engine is used with. It being understood that the motoring time $t_{motoring}$ of the modified start sequence may be in a range of 0 seconds to minutes, which, of course, depends on the values of $T_{core\ shutdown}$, $t_{shutdown}$, and t_{start}.

In an alternate embodiment, the modified start sequence may only be run when the bowed rotor start risk model **206** has determined that the motoring time $t_{motoring}$ is greater than zero seconds upon receipt of a start command given to the engine **10**. In this embodiment and if the bowed rotor start risk model **206** has determined that $t_{motoring}$ is not greater than zero seconds, a normal start sequence will be initiated upon receipt of a start command to the engine **10**.

Accordingly and during an engine command start, the bowed rotor start risk model **206** of the system **200** is automatically referenced wherein the bowed rotor start risk model **206** correlates the elapsed time since the last engine shutdown time and the shutdown heat state of the engine **10** as well as the current start time t_{start} in order to determine the duration of the modified start sequence wherein motoring of the engine **10** at a reduced speed N_{target} without fuel and ignition is required. As used herein, motoring of the engine **10** in a modified start sequence refers to the turning of a starting spool by the starter **120** at a reduced speed N_{target} without introduction of fuel and an ignition source in order to cool the engine **10** to a point wherein a normal start sequence can be implemented without starting the engine **10** in a bowed rotor state. In other words, cool or ambient air is drawn into the engine **10** while motoring the engine **10** at a reduced speed in order to clear the "bowed rotor" condition, which is referred to as a dry motoring mode.

The bowed rotor start risk model **206** can output the motoring time $t_{motoring}$ to a motoring controller **208**. The motoring controller **208** uses a dynamic control calculation in order to determine a required valve position of the starter valve **116**A, **116**B used to supply an air supply or starter air supply **114** to the engine **10** in order to limit the motoring speed of the engine **10** to the target speed N_{target} due to the position of the starter valve **116**A, **116**B. The required valve position of the starter valve **116**A, **116**B can be determined based upon an air supply pressure as well as other factors including but not limited to ambient air temperature of the aircraft, parasitic drag on the engine **10** from a variety of engine driven components such as electric generators and hydraulic pumps, and other variables such that the motoring controller **208** closes the loop for an engine motoring speed target N_{target} for the required amount of time based on the output of the bowed rotor start risk model **206**. In one embodiment, the dynamic control of the valve position (e.g., open state of the valve (e.g., fully open, ½ open, ¼ open, etc.) in order to limit the motoring speed of the engine **10**) is controlled via duty cycle control (on/off timing using pulse width modulation) of electromechanical device **110** for discrete starter valve **116**A.

When the variable position starter valve **116**B of FIG. **3** is used, a valve angle **207** can be provided to motoring control **208** based on the valve angle feedback **112** of FIG. **3**. A rotor speed N2 (i.e., speed of high speed spool **32**) can be provided to the motoring controller **208** and a mitigation monitor **214**, where motoring controller **208** and a mitigation monitor **214** may be part of controller **102**. Vibration data **132** can also be provided to mitigation monitor **214**.

The risk model **206** can determine a bowed rotor risk parameter that is based on the heat stored (T_{core}) using a mapping function or lookup table. When not implemented as a fixed rotor speed, the bowed rotor risk parameter can have an associated dry motoring profile defining a target rotor speed profile over an anticipated amount of time for the motoring controller **208** to send control signals **210**, such as valve control signals **150** for controlling variable position starter valve **116**B of FIG. **3**.

In some embodiments, an anticipated amount of dry motoring time can be used to determine a target rotor speed profile in a dry motoring profile for the currently observed conditions. As one example, one or more baseline characteristic curves for the target rotor speed profile can be defined in tables or according to functions that may be rescaled to align with the observed conditions. An example of a target rotor speed profile **1002** is depicted in graph **1000** of FIG. **12** that includes a steep initial transition portion **1004**, followed by a gradually increasing portion **1006**, and a late acceleration portion **1008** that increases rotor speed above a critical rotor speed, through a fuel-on speed and an engine idle speed. The target rotor speed profile **1002** can be rescaled with respect to time and/or select portions (e.g., portions **1004**, **1006**, **1008**) of the target rotor speed profile **1002** can be individually or collectively rescaled (e.g., slope changes) with respect to time to extend or reduce the total motoring time. The target rotor speed profile **1002** may include all positive slope values such that the actual rotor speed **1010** is driven to essentially increase continuously while bowed rotor start mitigation is active. While the example of FIG. **12** depicts one example of the target rotor speed profile **1002** that can be defined in a dry motoring profile, it will be understood that many variations are possible in embodiments.

An example of the effects of bowed rotor mitigation are illustrated in graph **420** of FIG. **7** that depicts a normal or cooled engine start (line **432**) versus a bowed rotor or mitigated engine start (line **434**) in accordance with one non-limiting embodiment of the disclosure. At point **436**, a pilot or operator of the engine **10** sets or initiates a start command of the engine. At point **438** and after the start command is initiated, the controller **102**, based upon the risk model **206**, requires the engine to motor at a pre-determined speed ($N_{pre\text{-}determined}$ or N_{target}), which is less than a normal idle start speed N2 for a time ($t_{determined}$). The pre-determined speed ($N_{pre\text{-}determined}$ or N_{target}) can be defined within a predetermined speed range $N_{targetMin}$ to $N_{targetMax}$ that is used regardless of the calculated time period $t_{motoring}$ for homogenizing engine temperatures. The time period $t_{determined}$ is based upon the output of the risk model **206**. The determined speed ($N_{pre\text{-}determined}$ or N_{target}) is achieved by controlling the operational position of starter valve **116**A, **116**B. Thereafter and at point **440** when the required motoring time (determined from the risk model **206**) has been achieved, such that the "bowed condition" has been cleared a normal start sequence with a normal speed **N2** is initiated. Subsequently and at point **442**, the idle speed **N2** has been achieved. This modified sequence is illustrated in one non-limiting manner by the dashed line **434** of the graph **420** of FIG. **7**. It is, of course, understood that ($t_{determined}$) may vary depending upon the outputs of the risk model **206**, while $N_{pre\text{-}determined}$ or N_{target} is a known value. Of course, in alternative embodiments, the risk model **206** may be configured to provide the speed of the engine **10** during a modified start sequence. Still further and as mentioned above, the starter valve may be dynamically varied based upon the outputs of the risk model **206** as well as the pressure of the air supply **114** in order to limit the motoring speed of the engine **10** to that of $N_{pre\text{-}determined}$ or N_{target} during the clearing of a bowed rotor condition. Line **432** illustrates a normal start sequence wherein the time $t_{determined}$ is zero for a modified start as determined by the risk model **206**.

The example of FIG. **11** illustrates how a valve angle command **902** can be adjusted between 0 to 100% of a commanded starter valve opening to generate the actual rotor speed **1010** of FIG. **12**. As the actual rotor speed **1010** tracks to the steep initial transition portion **1004** of the target rotor speed profile **1002**, the valve angle command **902** transitions through points "a" and "b" to fully open the variable position starter valve **116**B. As the slope of the target rotor speed profile **1002** is reduced in the gradually increasing portion **1006**, the valve angle command **902** is reduced between points "b" and "c" to prevent the actual rotor speed **1010** from overshooting the target rotor speed profile **1002**. In some embodiments, decisions to increase or decrease the commanded starter valve opening is based on monitoring a rate of change of the actual rotor speed **1010** and projecting whether the actual rotor speed **1010** will align with the target rotor speed profile **1002** at a future time. If it is determined that the actual rotor speed **1010** will not align with the target rotor speed profile **1002** at a future time, then the valve angle of the variable position starter valve **116**B is adjusted (e.g., increase or decrease the valve angle command **902**) at a corresponding time. In the example of FIGS. **11** and **12**, the valve angle command **902** oscillates with a gradually reduced amplitude between points "c", "d", and "e" as the actual rotor speed **1010** tracks to the target rotor speed profile **1002** through the gradually increasing portion **1006**. As dry motoring continues, the overall homogenization of the engine **10** increases, which allows the actual rotor speed **1010** to safely approach the critical rotor speed without risking damage. The valve angle command transitions from point "e" to point "f" and beyond to further increase the actual rotor speed **1010** in the late acceleration portion **1008** above the critical rotor speed, through a fuel-on speed and an engine idle speed. By continuously increasing the actual rotor speed **1010** during dry motoring, the bowed rotor condition can be reduced faster than holding a constant slower speed.

As one example of an aircraft that includes systems as described herein, mission risk factor model **204** may run on controller **102** of the aircraft to track heat stored (T_{core}) in the turbine at the time of engine shutdown. Modeling of potential heat stored in the system may be performed as a turbine disk metal temperature model in the mission risk factor model **204**. When the aircraft lands, engines typically operate at idle for a cool down period of time, e.g., while taxiing to a final destination. When an engine shutdown is detected, model state data can be logged by the DSU **104** prior to depowering. When the controller **102** powers on at a later time and model state data can be retrieved from the DSU **104**, and the bowed rotor start risk model **206** can be updated to account for the elapsed time. When an engine start is requested, a bowed rotor risk can be assessed with respect to the bowed rotor start risk model **206**. Extended dry motoring can be performed during an engine start process until the bow risk has sufficiently diminished. If a safety condition is detected by the controller **102**, for instance, a notification that maintenance will be performed, an abort signal **220** can be triggered to halt dry motoring.

In reference to FIGS. **4** and **12**, the mitigation monitor **214** of FIG. **4** can operate in response to receiving a complete indicator **212** to run a verification of the bowed rotor mitigation. The mitigation monitor **214** can provide mitigation results **216** to the motoring controller **208** and may provide result metrics **218** to other systems, such a maintenance request or indicator. Peak vibrations can be checked by the mitigation monitor **214** during the start processes to confirm that bowed rotor mitigation successfully removed the bowed rotor condition. The mitigation monitor **214** may also run while dry motoring is active to determine whether adjustments to the dry motoring profile are needed. For example, if a greater amount of vibration is detected than was expected, the mitigation monitor **214** can request that the motoring controller **208** reduce a slope of the target rotor speed profile **1002** of FIG. **12** to extend the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed. Similarly, if the magnitude of vibration observed by the mitigation monitor **214** is less than expected, the mitigation monitor **214** can request that the motoring controller **208** increase a slope of the target rotor speed profile **1002** of FIG. **12** to reduce the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed.

FIG. **5** is a flow chart illustrating a method **300** of bowed rotor start mitigation of a gas turbine engine in accordance with an embodiment. The method **300** of FIG. **5** is described in reference to FIGS. **1-12** and may be performed with an alternate order and include additional steps. At block **302**, the controller **102** receives at least one aircraft-based parameter **202** on aircraft communication bus **106**. At block **304**, the controller **102** determines at least one inferred engine operating thermal parameter (e.g., T_{core}) from the at least one aircraft-based parameter **202** (e.g., TLA). The at least one inferred engine operating thermal parameter can be selected from data describing a history of the aircraft before an engine shutdown.

At block **306**, the controller **102** controls the motoring system **108**, **108**A to drive rotation of a starting spool of the gas turbine engine **10** below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected threshold. The preselected threshold may be a value or range where a greater risk of a bowed rotor condition exists. The motoring system **108**, **108**A can be controlled as described above depending on the system implementation. The controller **102** may transmit a notification on the aircraft communication bus **106** that the gas turbine engine **10** is being conditioned for starting to inform aircraft crew and/or a test stand operator. The time since the engine shutdown $t_{shutdown}$ can be used to modify a time of rotation for dry motoring. If time data is unavailable from the DSU **104**, dry motoring can be performed for a maximum expected time assuming worst case conditions.

If the controller **102** detects a safety condition (which may include data received on the aircraft communication bus **106**) while dry motoring is active, the controller **102** can trigger abort signal **220** to abort rotation of the starting spool. A braking torque may be applied to the starting spool to abort rotation of the starting spool based on the abort signal **220**. The controller **102** can also monitor for rotary motion of the shaft using a rotation sensor, such as speed pickup **122** or an alternate sensor that detects rotor speed **N2**. The controller **102** can trigger removal of power from the motoring system **108**, **108**A based on detecting rotary motion of the starting spool above a target speed (e.g., target speed N_{target}). For example, dry motoring may not be needed if wind or other forces drive rotation of the high speed spool **32**.

In embodiments, the risk model **206** can be used to determine a motoring time period $t_{motoring}$ for a start sequence of the gas turbine engine **10**, where the risk model **206** uses the recorded time of the engine shutdown and the stored heat state of the gas turbine engine **10** at shut down to determine the motoring time period $t_{motoring}$. The gas turbine engine **10** is motored at a predetermined speed range of $N_{targetMin}$ to $N_{targetMax}$ during the motoring time period, which is less than a normal idle start speed **N2**. The controller **102** can dynamically vary a position of starter valve **116**A, **116**B during the motoring time period in order to motor the gas turbine engine **10** at the predetermined speed range of $N_{targetMin}$ to $N_{targetMax}$. The predetermined speed range of $N_{targetMin}$ to $N_{targetMax}$ may be tightly controlled to a substantially constant rotor speed or cover a wider operating range according to a dry motoring profile.

As one example with respect to FIGS. **3** and **12**, the variable position starter valve **116**B can be initially set to a valve angle of greater than 50% open when bowed rotor start mitigation is active. The controller **102** can monitor a rate of change of the actual rotor speed **1010**, project whether the actual rotor speed **1010** will align with the target rotor speed profile **1002** at a future time based on the rate of change of the actual rotor speed **1010**, and adjust a valve angle of the variable position starter valve **116**B based on determining that the actual rotor speed **1010** will not align with the target rotor speed profile **1002** at a future time.

Further dynamic updates at runtime can include adjusting a slope of the target rotor speed profile **1002** in the dry motoring profile while the bowed rotor start mitigation is active based on determining that a vibration level of the gas turbine engine **10** is outside of an expected range. Adjusting the slope of the target rotor speed profile **1002** can include maintaining a positive slope. Vibration levels may also or alternatively be used to check/confirm successful completion of bowed rotor start mitigation prior to starting the gas turbine engine **10**. For instance, based on determining that the bowed rotor start mitigation is complete, a vibration level of the gas turbine engine **10** can be monitored while sweeping through a range of rotor speeds including the critical rotor speed.

In further reference to FIG. **4**, the mitigation monitor **214** of FIG. **4** may receive a complete indicator **212** from the motoring controller **208** when the motoring controller **208** has completed dry motoring, for instance, if the motoring time has elapsed. If the mitigation monitor **214** determines that the bowed rotor condition still exists based on vibration data **132** collected, the motoring controller **208** may restart dry motoring, or a maintenance request or indicator can be triggered along with providing result metrics **218** for further analysis. Metrics of attempted bowed rotor mitigation can be recorded in the DSU **104** based on determining that the attempted bowed rotor mitigation was unsuccessful or incomplete.

Referring now to FIG. **8**, a graph **500** illustrating examples of various vibration level profiles **502** of an engine, such as gas turbine engine **10** of FIG. **1** is depicted. The vibration level profiles **502** represent a variety of possible vibration levels observed before and/or after performing bowed rotor mitigation. Critical rotor speed **510** is the speed at which a vibration peak is expected due to amplification effects of a bowed rotor condition along with other contributions to vibration level generally. A peak vibration **504** at critical rotor speed **510** may be used to trigger different events. For example, if the peak vibration **504** at critical rotor speed **510** is below a maintenance action threshold **506**, then no further actions may be needed. If the peak vibration **504** at critical rotor speed **510** is above a damage risk threshold **508**, then an urgent maintenance action may be requested such as an engine check. If the peak vibration **504** at critical rotor speed **510** is between the maintenance action threshold **506** and the damage risk threshold **508**, then further bowed rotor mitigation actions may be requested, such as extending/restarting dry motoring. In one embodiment, a maintenance request is triggered based on the actual vibration level exceeding maintenance action threshold **506** after completing an attempt of bowed rotor mitigation.

The lowest rotor vibration vs. speed in FIG. **8** (vibration profile **502**D) is for a fully homogenized rotor, where mitigation is not necessary (engine parked all night long, for example). The next higher curve shows a mildly bowed rotor and so on. The maintenance action threshold **506** is a threshold for setting a maintenance flag such as requiring a troubleshooting routine of one or more system elements. The damage risk threshold **508** may be a threshold to trigger a more urgent maintenance requirement up to and including an engine check. As dry motoring is performed in embodiments, the gas turbine engine **10** may shift between vibration profiles. For instance, when a bow rotor condition is present, the gas turbine engine **10** may experience vibration levels according to vibration profile **502**A, if mitigation is not performed. As dry motoring is run, the gas turbine engine **10** may have a vibration profile that is gradually reduced from vibration profile **502**A to vibration profile **502**B and then vibration profile **502**C, for example. By checking the current vibration level at a corresponding rotor speed with respect to time, the controller **102** can determine whether adjustments are needed to extend or reduce the slope of the target rotor speed profile **1002** of FIG. **12** depending on an expected rate of bowed rotor reduction. In embodiments, a slope of the target rotor speed profile **1002** in the dry motoring profile **206** can be adjusted and maintains a positive slope while bowed rotor start mitigation is active based on determining that a vibration level of the gas turbine engine **10** is less than a targeted maximum range **512**, which may define a safe level of vibration to ensure that no risk of a maintenance action or damage will likely occur if the actual rotor speed **1010** is increased faster than previously planned.

Accordingly and as mentioned above, it is desirable to detect, prevent and/or clear a "bowed rotor" condition in a gas turbine engine that may occur after the engine has been shut down. As described herein and in one non-limiting embodiment, the controller **102** may be programmed to automatically take the necessary measures in order to provide for a modified start sequence without pilot intervention other than the initial start request. In an exemplary embodiment, the controller **102** and/or DSU **104** comprises a microprocessor, microcontroller or other equivalent processing device capable of executing commands of computer readable data or program for executing a control algorithm and/or algorithms that control the start sequence of the gas turbine engine. In order to perform the prescribed functions and desired processing, as well as the computations therefore (e.g., the execution of Fourier analysis algorithm(s), the control processes prescribed herein, and the like), the controller **102** and/or DSU **104** may include, but not be limited to, a processor(s), computer(s), memory, storage, register(s), timing, interrupt(s), communication interfaces, and input/output signal interfaces, as well as combinations comprising at least one of the foregoing. For example, the controller **102** and/or DSU **104** may include input signal filtering to enable accurate sampling and conversion or acquisitions of such signals from communications interfaces. As described above, exemplary embodiments of the disclosure can be implemented through computer-implemented processes and apparatuses for practicing those processes.

While the present disclosure has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the present disclosure is not limited to such disclosed embodiments. Rather, the present disclosure can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the present disclosure. Additionally, while various embodiments of the present disclosure have been described, it is to be understood that aspects of the present disclosure may include only some of the described embodiments. Accordingly, the present disclosure is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A bowed rotor start mitigation system for a gas turbine engine of an aircraft, the bowed rotor start mitigation system comprising:

a motoring system; and

a controller coupled to the motoring system and an aircraft communication bus, wherein the controller is configured to perform:

determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, wherein the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown; and

controlling the motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

2. The bowed rotor start mitigation system as in claim **1**, wherein the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.

3. The bowed rotor start mitigation system as in claim **1**, wherein a time since the engine shutdown is used to modify a time of rotation of the starting spool by the motoring system.

4. The bowed rotor start mitigation system as in claim **1**, wherein the controller transmits a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.

5. The bowed rotor start mitigation system as in claim **1**, wherein the controller is configured to abort rotation by the motoring system when a safety condition is detected.

6. The bowed rotor start mitigation system as in claim **5**, wherein the motoring system is configured to apply a braking torque to the starting spool to abort rotation of the starting spool.

7. The bowed rotor start mitigation system as in claim **1**, further comprising a rotation sensor for detecting rotary motion of the starting spool, and the controller is further coupled to the rotation sensor.

8. The bowed rotor start mitigation system as in claim **7**, wherein the controller is configured to remove power from the motoring system based on detecting rotary motion of the starting spool above a target speed.

9. The bowed rotor start mitigation system as in claim **1**, wherein a vibration monitor is used to set a maintenance flag based on detecting a vibration level that exceeds a maintenance action threshold while accelerating the starting spool of the gas turbine engine.

10. The bowed rotor start mitigation system as in claim **1**, wherein the at least one inferred engine operating thermal parameter comprises an engine temperature value, and the at least one aircraft-based parameter received on the aircraft communication bus comprises a throttle lever angle profile.

11. A method of bowed rotor start mitigation for a gas turbine engine of an aircraft, the method comprising:

determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on an aircraft communication bus, wherein the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown; and

controlling a motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

12. The method as in claim **11**, wherein the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.

13. The method as in claim **11**, further comprising:

modifying a time of rotation of the starting spool by the motoring system based on a time since the engine shutdown.

14. The method as in claim **11**, further comprising:

transmitting a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.

15. The method as in claim **11**, further comprising:

aborting rotation by the motoring system when a safety condition is detected.

16. The method as in claim **15**, further comprising:

applying a braking torque to the starting spool to abort rotation of the starting spool.

17. The method as in claim **11**, further comprising:

detecting rotary motion of the starting spool using a rotation sensor.

18. The method as in claim **17**, further comprising:

removing power from the motoring system based on detecting rotary motion of the starting spool above a target speed.

19. The method as in claim **11**, further comprising:

setting a maintenance flag based on a vibration monitor detecting a vibration level that exceeds a maintenance action threshold while the starting spool of the gas turbine engine accelerates.

20. The method as in claim **11**, wherein the at least one inferred engine operating thermal parameter comprises an engine temperature value, and the at least one aircraft-based parameter received on the aircraft communication bus comprises a throttle lever angle profile.

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